

## DESIGN AND ANALYSIS OF MICRO GAS TURBINE AS A RANGE EXTENDER IN AN ELECTRIC VEHICLES

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### ABSTRACT

Range extender increases the driving range of electric vehicles. The most commonly used range extenders are internal combustion (IC) engines, fuel-cells, and micro gas turbines (MGT). The range extender drives an electric generator which charges a battery supplying the vehicle's electric motor with electricity. This arrangement is known as a series hybrid powertrain. Amongst different kinds of range extenders, MGT provides a better solution for combined power generation and heat applications. Compared to an IC engine, it has a higher power density, can run on variety of fuel, has lower energy loss and a reasonable fuel efficiency. Similarly, if compared to fuel cells for automobiles, MGT facilitates long as well as short journeys with small battery packs, which ultimately can reduce capital and high maintenance cost of batteries. Apart from the advantages, MGT has geometrical and performance issues when it comes to small-scale design, which drops its overall efficiency. These effects are studied by detailed modeling and simulation using Gas Turbine Simulation Program (GSP) and MATLAB. Selection of MGT as on board device is due to its small size and power to weight ratio. The purpose of this study is to facilitate Electric Vehicles (EV) with best possible MGT size as on board charging device. MGT will be used to charge batteries to drive EV up to desired range. Comparison between sizing of battery and micro gas turbine is critical outcome of this research.

*Keywords — micro gas turbine, electric vehicles, on-board charging device, driving range, range extender.*

### 1. INTRODUCTION

Manufacturing of Electric vehicles has become primary business for automobile industries. Introduction and adaption of electric vehicles is turning to be governments' priority worldwide to maintain clean environment. Tesla is one of the

biggest name to lead electric vehicles development in automobile world.

US is achieving its target to electrify their cars till 2025. Europe has to reduce 40% transport sector's impact on the environment by 2030. Global sales of new electric vehicles topped a million units for the first time in 2017 but that milestone was largely driven by mass expansion in China, whose market is now larger than Europe and the United States combined. Germany is about to become the first major country to set an official deadline for a ban on gas-powered cars. They aim at making all passenger vehicles emission-free by 2050. [7,8]

Similarly, India has started to produce electric vehicles to minimize usage of fossil fuel. Even Pakistan's government is welcoming electric vehicles in order to fight against global warming and minimize fuel consumption of transport sector.

Main source to power electric vehicles are batteries. Production of batteries has been increased at similar rate of electric vehicles. Charging of batteries is another attention seeker for consumers and producers. Developers have tried many sources to facilitate battery charging. These sources include plug in chargers for homes, instant chargers and on board charging devices, also known as range extenders.

MGT as a range extender provides potential solution to extend the driving range of electric vehicles. They range from hand held units producing less than a kilowatt, to commercial sized systems that produce tens or hundreds of kilowatts. [1,2]

#### 1.1. MICRO GAS TURBINE TECHNOLOGY

**Micro Gas Turbine (MGT)** are a relatively new type of combustion turbines that can produce both heat and electricity on a small scale. Their size varies from small scale units like models crafts to heavy supply like power supply to hundreds of households. [3,4]

MGT offers an efficient solution for standalone electricity generation system and onboard charging device for Electric Vehicles. This study focuses the design and analysis of micro turbine to enhance driving ranges and minimizes cost for batteries in an electric vehicle.

Famous names in the production of MGTs are MTT, Delta motorsports, Bladon Jets and Capstone. They have claimed 25-30% maximum efficiency achieved. Small scale design issues are noted in its development. [9,10]

### 1.2. NATURE OF ISSUES

Presently, hybrid vehicles carry large battery packs with them to extend their driving ranges. These batteries are expensive to maintain and take a long time to recharge (approx. 6-7 hours). On average people drive short distances per day, so carrying expensive and heavy batteries is not a viable solution. Also it increases cost of vehicle. Automobiles need more electrification than to be added more batteries in it so that industries can build light weight vehicles. MGT can allow to reduce the cost of batteries and provide the power on need basis.

MGTs as Range Extender have been introduced in Electric Vehicles (EV) but their performance is not that enough due to small scale design of turbomachinery which leads to higher geometrical effects. These effects cause less component efficiencies and low performance running. Similar to design and mechanical issues, these machines face packaging problems when it comes to installation in an engine room of car.

### 1.3. SCOPE OF WORK

During the last few decades, several attempts have been made to develop MGT with efficiency levels close to those of larger gas turbines. Various remarkable implementation has been done to establish MGTs for small scale applications particularly below 100 kW, many progresses have failed to be successful for achieving sufficient efficiency, reliability, and cost effectiveness for the market. Small-scale effects are main technical hurdle for its success.

This paper scopes to design such micro scale gas turbine while considering its small scale effects. So that it can facilitate an electric vehicle more conveniently to drive on short as well as on long journeys. For which gas turbine simulation (GSP) is used to optimize its cycle efficiency. Besides designing, matching and compatibility with batteries have been studied and calculated to predict on different sizes.

### 1.4. METHODOLOGY

This study is based on Tesla Model P85D as a hypothetical case. In which, a 47 kW recuperated Micro Gas Turbine is suggested with compatible battery size of 20 kWh energy to characterize 100 kilometers range. In the first phase of study, battery sizing and charging analogy have been calculated to avail desired driving range. The performance output curves for Range and charging time vs speed are shown graphically which can be seen later on in this paper. Moving on to second phase, MGT modeling and simulations were done on gas turbine simulation program (GSP) by considering reference model CAPSTONE C30. This designing is followed by cycle optimization with the help of each component characteristics to avail maximum respective efficiencies. From these results both (Battery Pack and MGT) were matched together for multiple compatibilities.

### 2. BATTERY BANK SIZING

Tesla Model P85D's original driving range is 510 km having battery bank of 85 kWh. Its battery bank weighs 540 kg which is almost 1/4<sup>th</sup> of total weight of the car. We are going to reduce the size of battery bank which can give a range of almost 100 km. A battery bank to deliver desired range has been calculated with the help of following equations and output result is shown in table 1.

Calculation sequence is shown in figure 1.

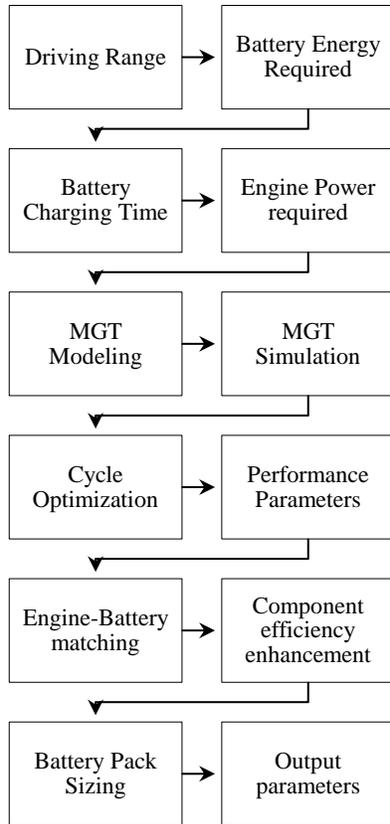


Figure 1 Battery Sizing

Following is the set of equation for detailed battery pack calculation.

Battery energy will be,

$$E = Q * V \quad (1)$$

Energy Density of battery can be determined with the help of power and physical volume

$$\rho = \frac{P}{vol} \quad (2)$$

$$I = Q * C \quad (3)$$

$$t = \frac{I}{Q} \quad (4)$$

$$n_{total\ cells} = n_{cells\ in\ one\ series} * n_{series} \quad (5)$$

$$V_p = n_{series} * V_c \quad (6)$$

$$I_s = I_c * n_{series} \quad (7)$$

$$Q_p = t * I_s \quad (8)$$

$$I_s = V_s * Q_s \quad (9)$$

$$W_{batteries} = W_{cell} * n_{cell} \quad (10)$$

Weight of battery pack = Weight of batteries x 1.47 (packing factor)

$$W_p = W_{batteries} * 1.47 \quad (11)$$

From these equations, battery pack calculations are done for different sizes and showing respective energies.

<u>Battery Bank Charging &amp; Discharging Estimation</u>					
Capacity of one cell	4	4	4	4	Ah
Avg. Discharge Voltage of one cell	3.4	3.4	3.4	3.4	V
Energy Capacity of one cell	13.6	13.6	13.6	13.6	Wh
Height of cell	64.93	64.93	64.93	64.93	Mm
Diameter of cell	18.2	18.2	18.2	18.2	Mm
Volume of one cell (mm3)	16894.07	16894.07	16894.07	16894.07	mm <sup>3</sup>
Volume of one cell (L)	0.02	0.02	0.02	0.02	L
Energy Density of one cell	805.02	805.02	805.02	805.02	Wh/L
Charge Rate	2	2	2	2	Cr
Max Charge current of one cell	8	8	8	8	A
Time of charging (hr)	0.5	0.5	0.5	0.5	Hr
Time of charging (min)	30	30	30	30	min
Number of cells in series	94	94	94	94	cells
Number of series in parallel	15	17	19	21	series
Number of total cells	1410	1598	1786	1974	cells
Voltage of battery pack	319.6	319.6	319.6	319.6	Volt

Current of the battery pack	120	136	152	168	A
Capacity of battery pack	60	68	76	84	Ah
Energy of battery pack	19.18	21.73	24.29	26.85	kWh
Weight of one cell	54	54	54	54	g
Weight of batteries	76.1	86.3	96.4	106.6	kg
Weight of battery pack	111.9	126.8	141.8	156.7	kg

Table 1: Battery Sizing

Table 1 shows various batteries with respect to different energies and weight. Increasing energy cause increment in weight of battery pack.

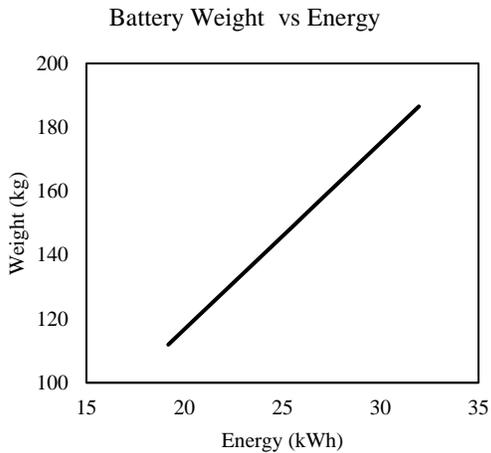


Figure 2 Battery weight vs Energy chart

Figure 2 shows battery bank weight increases with increasing energy due to increase in number of cells.

### 3. CHARGING ANALOGY

Charging analogy has been calculated to identify charging time with respect to average driving speed and power consumption. These analogies have been calculated according to power consumption behavior of tesla car given by Tesla Motors Club. [6] Speed vs power consumption profile of Tesla Model S is given in figure 2.

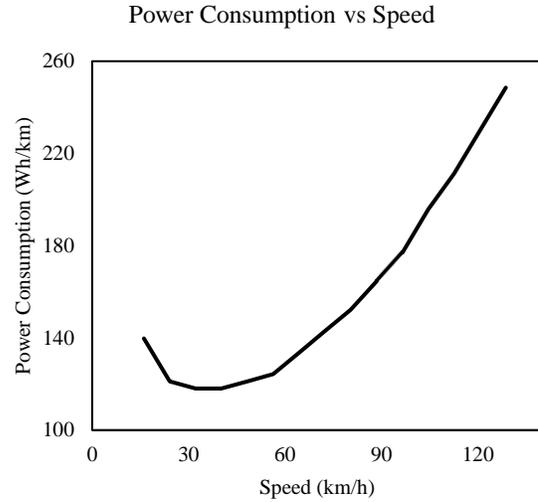


Figure 3: Power consumption vs speed chart copied from Tesla Motors [6]

Figure 3 tells power consumption of tesla car on different speeds. Firstly, it decreases from 10 km/hr to 40 km/hr then it increases onwards. By considering this behavior, driving range on various speeds have been calculated. Detailed analysis for various factors is given in this paper.

Ranges are calculated on different batteries. It is therefore to identify performance of vehicle's driving range.

Driving Range can be calculated on different power consumption withdrawn from respective batteries which is given as

$$R = E * PC \quad (12)$$

These calculations are done by keeping similar speed series. Graphical representation is given in figure 3;

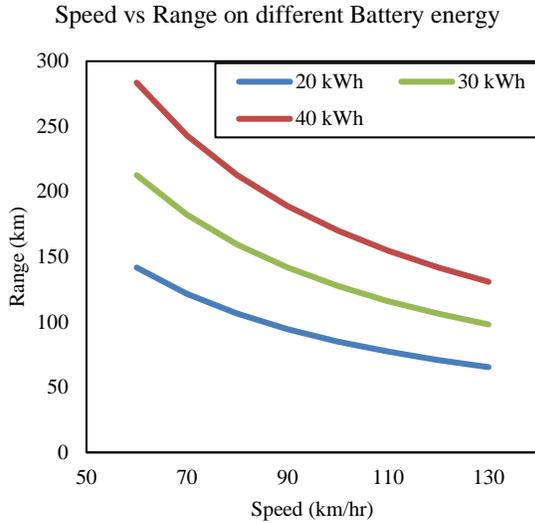


Figure 4: Calculated Range vs Speed Chart

Figure 4 shows, it can be seen that driving range is inversely proportional to driving speed. Power consumption increases due to increases in speed results in escalation of discharge rate, hence overall driving range is decreased. Power consumption on different speed have been calculated which shows traveling in cities should be kept under 80 km/hr in order to maintain driving range around 100 kilometers with 20 kWh battery pack. If same battery pack will be used for highway traveling, it will give 70 kilometers of driving range. Instead of using smaller one, 30 – 40 kWh battery could be used.

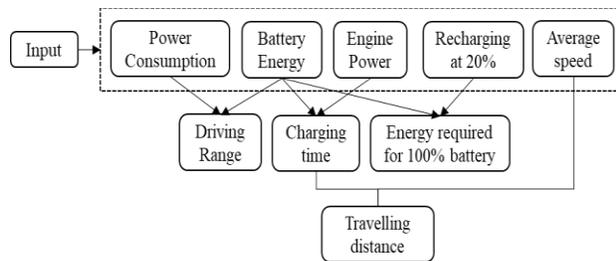


Figure 5: Charging analogy process

Charging time analogy calculations are being done with the help of following set of equations.

Input parameters for these calculations are included power consumption, battery energy, engine power, recharging point and average speed.

Recharging of battery pack will be started when it will be left with 20% energy.

$$\text{Remaining energy after 80\% drainage} = \text{Battery energy} \times 20\% \quad (13)$$

Distance travelled when engine is ON = Travel time when engine is ON x car average speed

$$d_{\text{engine ON}} = t_{\text{engine ON}} * S \quad (14)$$

Travel time for ON engine = Battery energy x Engine power

$$t_{\text{engine ON}} = E * P \quad (15)$$

Energy required for ON engine = power consumption x traveling distance for ON engine

$$E_{\text{engine ON}} = PC * d_{\text{engine ON}} \quad (16)$$

Total charging required = Energy need for 100% battery + energy require for ON engine

$$\text{charging time} = \frac{\text{total charging required}}{\text{Engine Power}} \quad (18)$$

Travel distance for OFF engine = driving range x 80%

$$d_{\text{engine OFF}} = R * 0.8 \quad (19)$$

Travel time for OFF engine = car average speed / travel distance for OFF engine

$$t_{\text{engine OFF}} = \frac{s}{d_{\text{engine OFF}}} \quad (20)$$

Charging time calculation may be represented in tabular form as given in table 2. This reference table is representing all calculations on different from 60 to 120 km/hr. These are different speeds according to our national traffic scenario. In cities, people usually drive under 80 km/hr. On national highways, driving speed is noted around 80-100 km/hr while as on motorways average speed of car is 120 km/hr.

<u>Charging time analogy for different speeds</u>					
<u>Car average speed</u>	<u>60</u>	<u>80</u>	<u>100</u>	<u>120</u>	<u>km/hr</u>
Power Consumption	128.0	150.4	188.1	225.74	Wh/km
Battery energy	20	20	20	20	kWh
Engine Power	47	47	47	47	kW
Recharging start at	20%	20%	20%	20%	
Driving Range	156.2	132.9	106.3	88.60	km
After drainage of	4	4	4	4	kWh

battery up to 20% For 100%, battery needs	16	16	16	16	kWh
Travelling Time for ON Engine	25.53	25.53	25.53	25.53	min
Travelling Distance for ON Engine	25.53	34.04	42.55	51.06	km
Charging require when Engine is ON	3.27	5.12	8.00	11.53	kWh
Total Charging required	19.27	21.12	24.00	27.53	kWh
Total charging time	24.60	26.97	30.64	35.14	Min
Travelling Time for OFF engine	125.0	0	79.74	51.03	35.44
Travelling Distance for OFF engine	125.0	106.3	85.05	70.88	Km

Table 2: Charging Time Analogy

Charging time changes with the change in engine power on same speed. Following chart shows multiple profiles of charging time on respective speed for different engines. Bigger engines help to increase rate of charging as given in the figure 4.

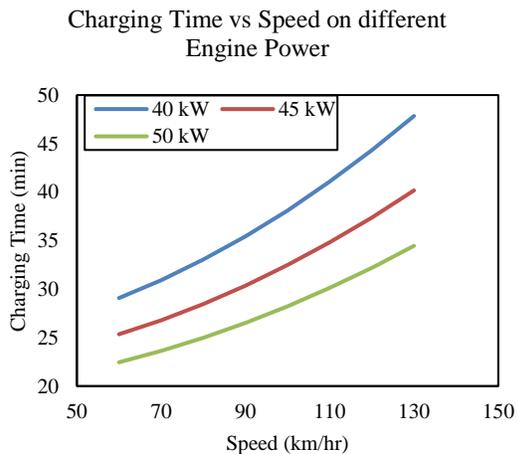


Figure 6: Charging Time vs Speed chart

From figure 6, the calculated battery specifications and power consumption, we need to have an on board charger that can charge around 30 minutes and battery can provide 70-100 kilometers driving range after charging. Micro gas turbine as on board charging device will be discussed below.

#### 4. MGT DESIGNING

In our case, we are dealing with 20 KWh battery to drive Hybrid Electric Vehicle to a range of 100 kilometers. For this purpose, we have to design a MGT of 45-50 KW to charge a battery pack within 30 minutes. As a reference model Capstone C30 is taken during this study. It was therefore necessary to obtain as much information about the micro turbine as possible. The design information is given in Appendix. Designing of MGT on Gas Turbine Simulation Program has been done by considering various parameters such as component efficiencies, national ambient conditions and other traveling needs. Conceptual design is given below.

##### MGT Design Parameters

###### Static / Total Ambient Conditions

Ambient Temperature = 315 K  
Ambient Pressure = 1.01325 bar  
Relative humidity = 67 %

###### Inlet

Design mass flow = 0.4 kg/s  
Pressure Ratio = 1

###### Compressor

Design Rotor Speed = 95000 rpm  
Design Efficiency = 75 %  
Heat transfer fraction = 0.5  
Pressure Ratio = 4

###### Recuperator

Effectiveness = 0.9  
Rel. total pressure loss:  
Flow 1 = 0.015  
Flow 2 = 0.04

###### Combustor

Design combustion efficiency = 0.999  
Design point rel. pressure loss = 0.02  
Exit Temp = 1200 K

###### Turbine

Design rotor speed = 95000 rpm  
Design efficiency = 0.82

Expansion heat loss fraction = 0.5

Exhaust

Velocity coefficient CV = 1

Thrust coefficient CX = 1

Throat CD = 1

Table 3 Specification sheet for MGT design on GSP

4.1. CONCEPTUAL DESIGN

Micro gas turbine has been designed and simulated numerically in GSP followed by MS EXCEL in order to present results in multiple formats.

4.1.1. MODELING

Gas Turbine Simulation Program (GSP) version 11 was used for cycle modeling. Figure 7 shows model diagram consisting of inlet, compressor, combustion chamber, recuperator and exhaust. Inlet and exhaust are used to define “starting” and “ending” of the model. This model has been configured with a recuperator to enhance its cycle efficiency. This MGT model has been used for conceptual design and component matching.

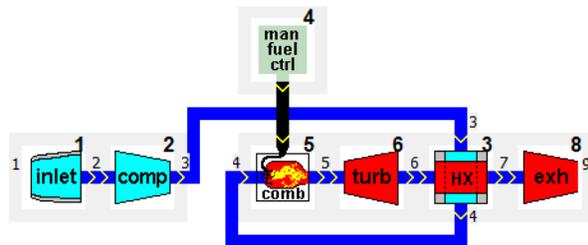


Figure 7: Conceptual design of MGT

4.1.2. DESIGN POINT

Gas turbine performance means Design Point Performance, Off-Design Performance and Transient Performance. Design Point Performance is central to the engine concept design process. Off-Design Performance is the steady state performance of gas turbine as its operational performance parameters are changing with time.

The design point is described as running at the particular speed, pressure ratio and mass flow for which the components were designed.

In any simulation session in GSP, the first step in determining the engine performance is the design point calculation. This step is used to size the model components which results in a defined geometry. The results serve as a reference point for off-design calculations. With the user-defined ambient conditions, the design point performance is determined by calculating the component

performances from the intake towards to the exhaust component.

4.2. ANALYSIS

Designing of micro gas turbine is done with reference model Capstone C30. Ambient conditions are taken into account according to Pakistan’s climate changes. Detailed modeling has been done by considering component efficiencies followed by cycle optimization.

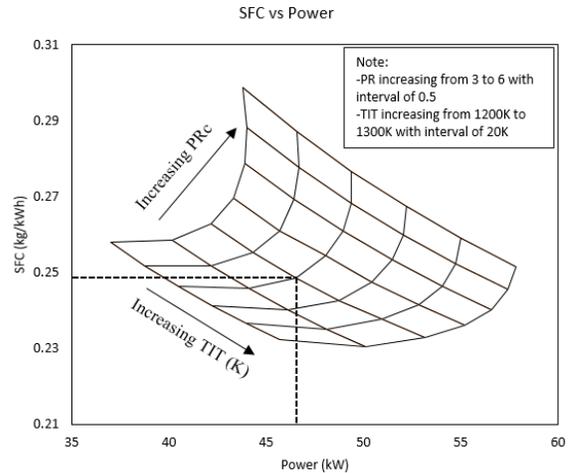


Figure 8: SFC vs Power chart

Figure 8 shows the results of cycle performance study with carpet plot between SFC and Power. It represents pressure and temperature behavior on several engine data points. Moving from left to right, temperature increases results in higher efficiency. Due to metallurgical limitations, we cannot increase our temperature beyond limits. Similarly increase in pressure vertically upward results in higher engine power allowing to an extent, beyond this limit SFC will be increased and engine power will remain constant. Carpet plot helped us to understand maximum engine power corresponds to SFC value.

To achieve optimum efficiency from figure 8, we are selecting 1240K and 4 as temperature and pressure ratio data lines respectively. On this interval engine power coming out to be 47 kW and SFC to be 0.25 kg/kWh.

In addition to SFC and Power, figure presents battery size compatibility to respective engine size. Each interval shows battery energy ranges from 16 kWh to 26 kWh. Selected interval states 20 kWh battery pack but due to conversion and distribution losses we will be taking 20 kWh including all tolerances.

A brief overview of battery energy vs power is given in figure 9;

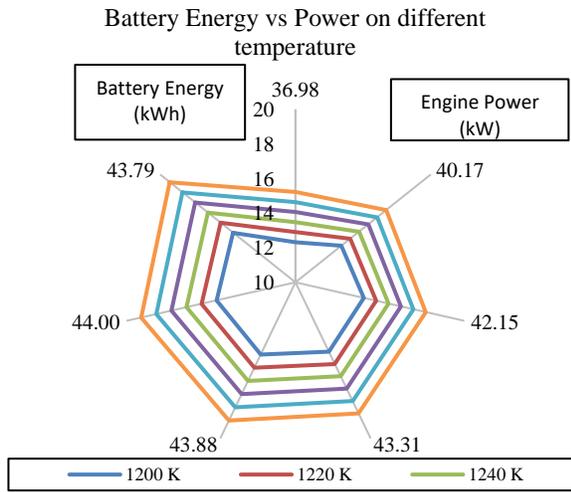


Figure 9: Battery energy vs Power chart

Battery energy compatibility increases with the increase in engine power. We have various options available by selecting 47 kilowatt engine power. But for machine design, metallurgical limitation and efficiency reduction limit temperature boundaries and SFC increase beyond specific point respectively.

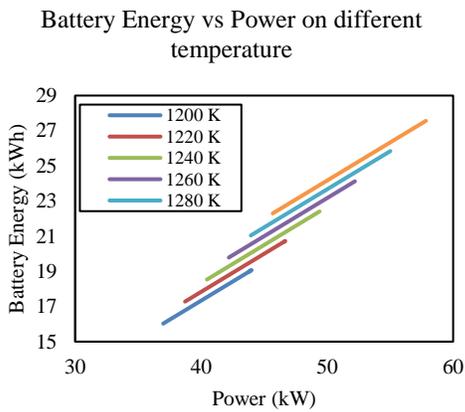


Figure 10: Battery energy vs Power consumption

In figure 10, temperature line is artificially elevated by 0.5 kWh to differentiate more clearly. It shows increment of battery energy due to increase in engine power. By selecting 1240K, it is noted that we have engine power available around 40 to 50 kWh. Each temperature line shows different engine ranges which can be seen separately in the following charts.

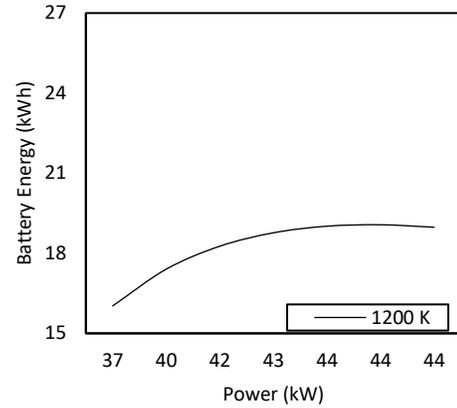


Figure 11: Battery energy vs Power for 1200K

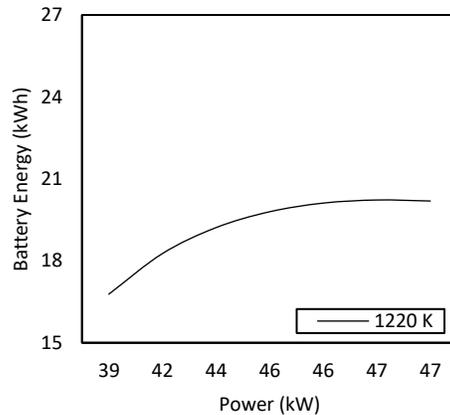


Figure 12: Battery energy vs Power for 1220K

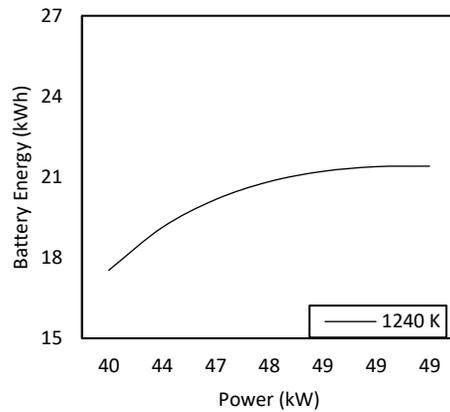


Figure 13: Battery energy vs Power for 1240K

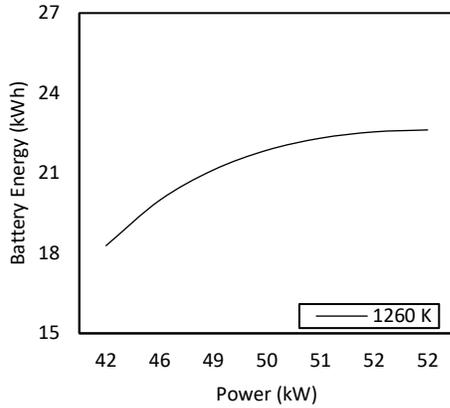


Figure 14: Battery energy vs Power for 1260K

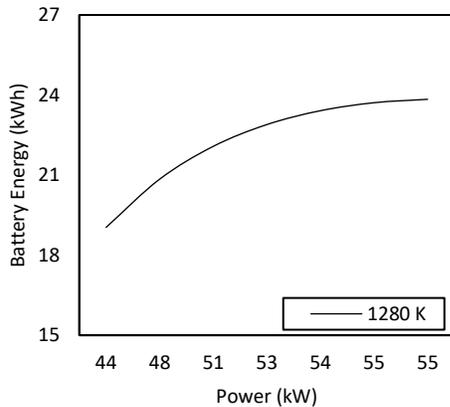


Figure 15: Battery energy vs Power for 1280K

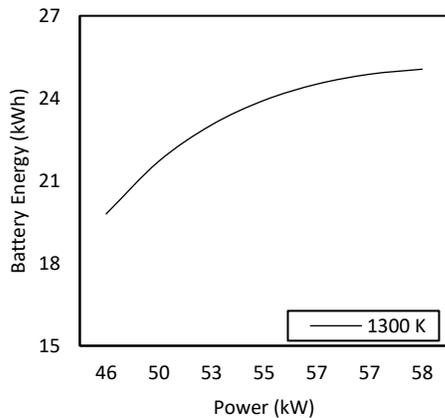


Figure 16: Battery energy vs Power for 1300K

This above study describes our main MGT model. Besides this model, several simulations have been run to identify behavior of micro gas turbine with respect to component design efficiencies and heat exchanger effectiveness.

#### 4.2.1. TURBINE DESIGN EFFICIENCY

Overall efficiency of MGT is influenced with turbine design efficiency because it helps to extract more work output from the working fluid by changing geometrical parameters. Different simulations are being run to check this feature is graphically represented in figure 17.

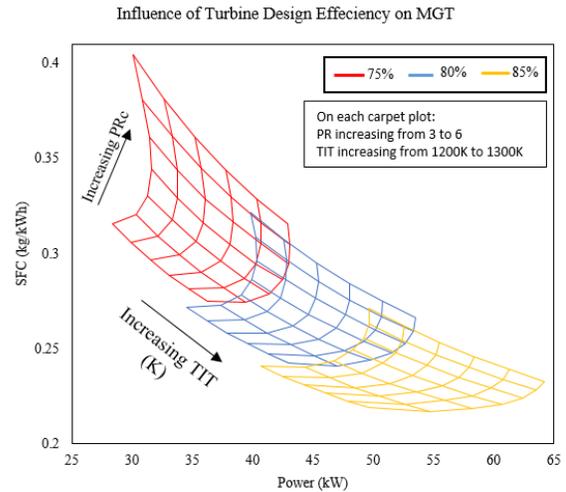


Figure 17: SFC vs Power on different Turbine Design Efficiency

#### 4.2.2. HEAT EXCHANGER EFFECTIVENESS

Growing demand for environmentally friendly gas-turbine engines with lower emissions and improved specific fuel consumption can be met by incorporating heat exchangers into gas turbines. It is noted that SFC is decreased when heat exchanger effectiveness is increased.

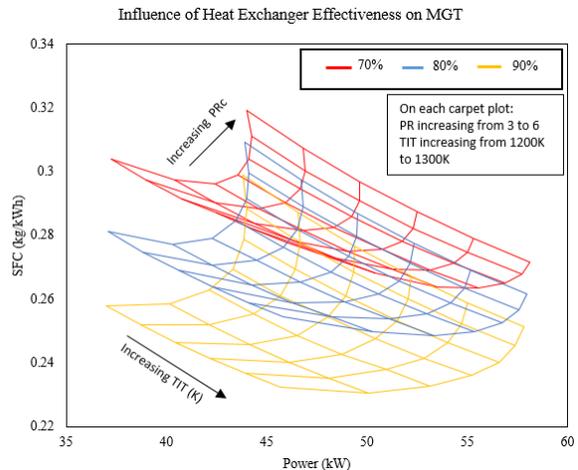


Figure 18: SFC vs Power on different HX effectiveness

#### 4.2.3. COMPRESSOR DESIGN EFFICIENCY

Similar to turbine design efficiency, compressor is fundamental part of gas turbine technology. Changes in compressor design efficiency cause overall performance of MGT. Some examples of compressor efficiencies are given below.

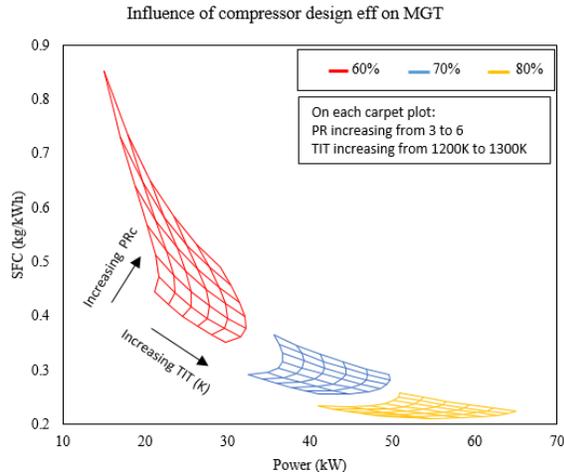


Figure 19: SFC vs Power on different compressor design eff

#### 5. RELEVANCE TO NATIONAL NEED

In Pakistan, transportation and traveling sector is the 2<sup>nd</sup> largest fuel consumer which is causing pollution and high cost of delivery goods as well as expensive traveling through personal conveyance. Government is emphasizing production / import of hybrid electric vehicles to reduce energy bill and pollution. This project will contribute towards further understanding of hybrid EV and assist in elegance design of MGT for automotive application. This project can be further extended into prototyping of MGT.

MGT installed electric vehicle will provide economical and environment friendly ride within the city as well as on highways.

#### 6. RESULT

In this study Tesla Model S P85 has been considered. We have concluded to replace its battery pack with 25 kWh capacity in order to achieve driving range of 100 km which is maximum daily requirement according to our national needs. Overall battery pack weight has been reduced to 130 kg. For that purpose, we should have a 45-50 kW MGT Engine as an on-board charging device.

#### 7. CONCLUSION

Currently MGT design has been established with battery sizing and charging configuration as mentioned in results section. Future work will be done

to validate our study by comparing it with the size (volume and weight) of micro turbine engine.

#### NOMENCLATURE

E	Battery energy
P	Battery Power
Q	Electric charge
$Q_s$	Electric charge of storage system
V	Voltage
$V_s$	voltage of storage system
$V_c$	voltage of one cell
I	charge current
$I_s$	charge current of storage system
$I_c$	charge current of one cell
$\rho$	energy density
vol	volume
c	charge rate
t	time of charging
n	number of cells
w	weight of batteries
R	Driving range
PW	Engine power
PC	power consumption
d	distance travelled
s	Car average speed
$\eta$	efficiency
$C_p$	specific heat at constant pressure
$C_v$	specific heat at constant volume
f	fuel / air ratio
h	specific enthalpy
$\Delta H$	enthalpy of reaction
M	mass flow
p	absolute pressure
Q	heat transfer per unit mass flow
r	pressure ratio
T	absolute temperature
t	temperature ration
W	specific work (power) output
Y	ratio of specific heat

#### Subscripts

c	cell
b	battery
p	battery pack

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