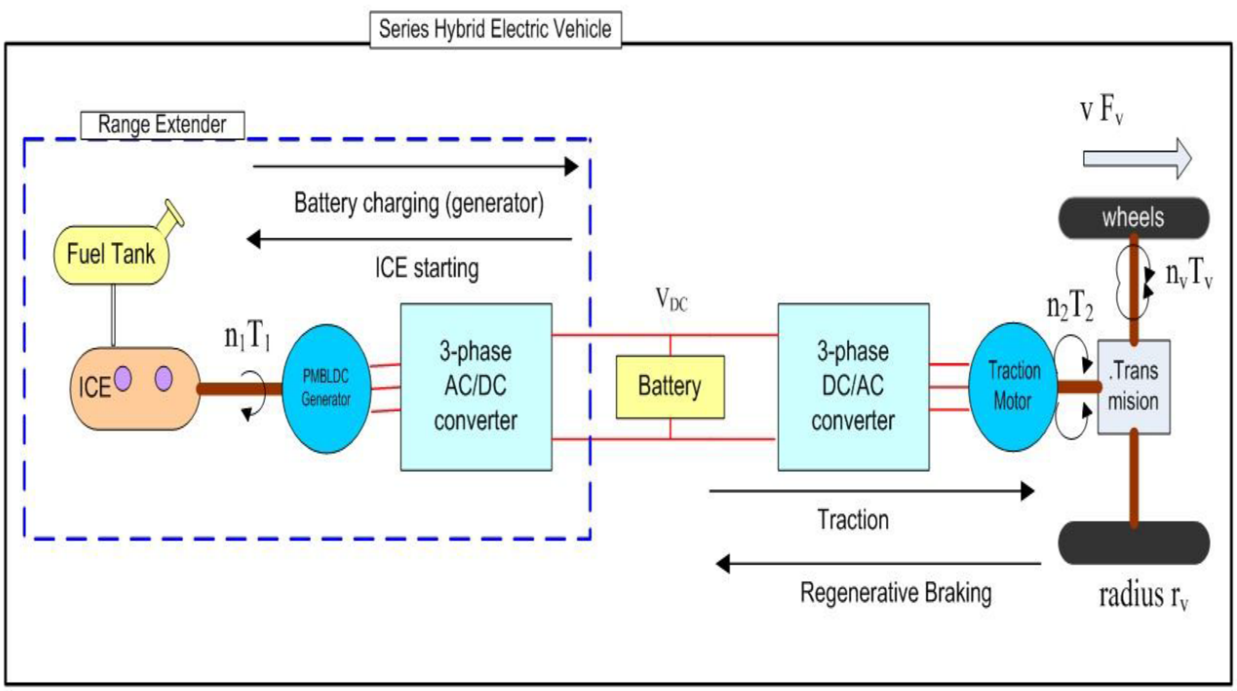
HAN Minor Project

Electric Hybrid & Fuel Cell Powertrains

MOTRAC, Sizing and Control of a Range Extender Using Wankel Engine



Group 3

HAN University of Applied Sciences

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Preface

This is the final report for the minor project "Sizing and Control of Range Extender (Wankel engine)". This report is made for the master's module Electric Hybrid and Fuel Cell Powertrains at the HAN University of Applied Sciences in Arnhem.

This final report contains the explanation on the work done to size and control the Wankel engine as a range extender. By proper literature research, calculations, modelling and simulation this has been achieved. The different backgrounds of the group members made this project an interesting experience. Through this project, all the group members aim to understand and simulate the behavior of a range extender in a controlled environment under various simulation scenarios.

The group would also like to thank the supervisor Ms. Aishwarya Aswal for her helpful tips, guidance and feedback throughout the project.

Arnhem, January 2021

Summary

This project is a part of the theoretical phase taught at the HAN University of Applied Sciences. In more detail, focusing on the sizing and control of the Wankel engine. The project is modelled and simulated using software AMESim. The complete model is created using AMESim library tree and control strategy for controlling the Wankel engine is developed with the help of literature papers. Several assumptions were considered to simplify the model.

A short background will describe about electric vehicles and study about the hybrid powertrains. This will be followed by the problem definition, objectives and the research questions. The approach on how to solve these questions and objectives will be described after that.

Sizing of a range extender is developed from the given load cycle requirement. Proper estimation and calculations are done for a better sizing by which it should be capable of generating the demand power.

AMESim is used for modelling. As it was one of the requirements from the customer. Once the model and control strategy been made results were compared with the load power cycle. This is also a validation where motor and battery should generate needed power.

The project group is able to produce desired results and also sized the range extender. Moreover, the estimation of fuel consumption is made and by making the engine to run at the best fuel-economical region.

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Introduction

1.1 Background:

Greenhouse gas emissions are one of the worst nightmares caused by the automotive industries. To overcome this challenge, many countries have decided to cut off the emissions by opting for renewable energy sources. The electric vehicles (EV) emerged very rapidly because of it the smaller carbon footprint compared to gasoline-power engines (Gebrehiwot, 2014). The range, however, is one of the main barriers for EV's, this is where the concept of range extenders originates. Range extenders are a bit different from EV's as it is a fuel-based auxiliary unit which extends the vehicle range by charging the vehicle's battery. The purpose of the combustion engine is it acts as a small generator for the batteries. It never drives the car's wheels directly and the complete driveline is driven by electric motor/generator (Gebrehiwot, 2014). This project deals with the sizing of an ICE and generator as compact as possible for an excavator. The ICE will provide the required amount of power to charge the battery when it is falling below the given state of charge. In this project, a Wankel engine is given as range extender (REx) as it can produce more power compared to a conventional engine as we need high weight to power ratio for an excavator.

Figure 1 explains a brief series hybrid transmission layout. The ICE will not directly be connected to the transmission, instead the ICE powers the generator which produces the current which then, either it can charge the battery in case it is low, or it may use to run motor directly through generator. The current from the battery will run the electric motors which help in overcoming the load.

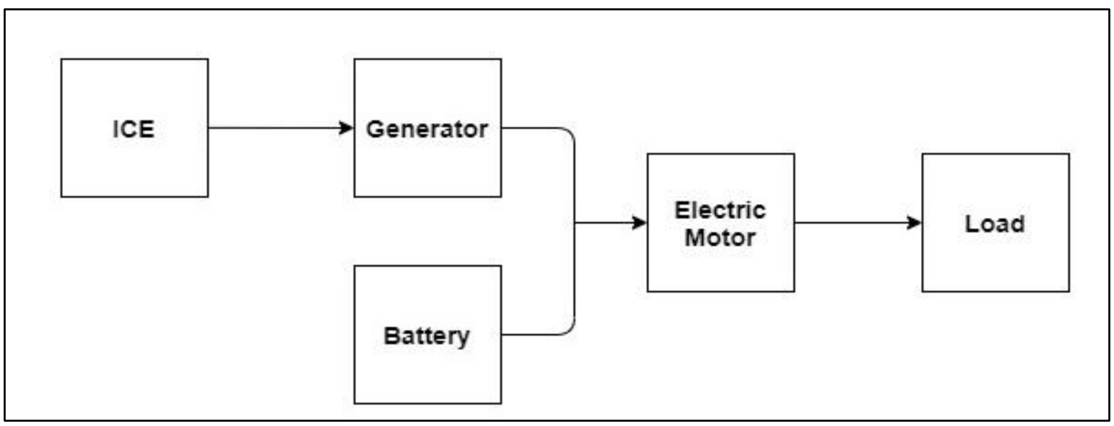


Figure 1: Basic layout of series hybrid transmission.

1.2 Problem Definition:

The major concern of using an electric vehicle is the range it can deliver. Also, the power supply during high load conditions is of utmost importance. Generally, EVs tend to struggle in these two areas and more intense research is being conducted around the world. A breakthrough for improving the range of the vehicle is through using a range extender, which is typically an internal combustion engine, turbine etc. Once the vehicle uses its battery pack and if SOC is going beyond the minimum value, it makes sure that the ICE will kick in. Range extenders come as an add-on to the vehicle and can be easily portable by attaching it to the front or rear of the vehicle.

In heavy-duty vehicles, where the workload is higher than that of the cars, the range extender plays a very crucial role by providing the required amount of power constantly and continuously throughout its work cycle. Hence sizing of a range extender is crucial.

1.3 Problem Objective:

The objective of this project is to size a Wankel engine, generator, and the additional auxiliary components, as a range extender according to the given load cycle and making it carbon neutral to a larger extent. In addition, a good control strategy will be developed to satisfy the power requirements by making the driveline work under the load cycle. Further estimation on the driveline efficiency will be made depending on fuel tank size. To achieve this objective in this project, AMESim software will be used.

1.4 Methodology and Approach

The following methods were strictly followed during the course of this particular project.

1. Literature review:
   One of the basic steps to successfully complete any project is to perform a literature survey. This helps in gaining additional knowledge about the driveline, different motor/generators properties, implementing the control strategy and furthermore. It also shares various perspectives in which the project can be realized. As the project progresses, more insight knowledge one needs to have, and it can be achieved by going through papers.
2. Sizing and Modeling:
   The next big stride is to size the range extender including the auxiliary components to a compactable size by calculations. Once sizing calculation is done, modelling of the component will be done based on their size and driveline.
3. Simulation and validation:
   Once the modelling portion is created, certain inputs will be fed to the model based on the customers' requirements and the obtained results are compared whether they are satisfactory by doing validation.
4. Conclusion and Discussion:
   After the results are drawn, the report concludes with the necessary conclusions and discussions for future prospects.

1.5 Restrictions

This project came up with a series of restriction which we had to consider while moving on with this project. The restrictions are mentioned below:

1. The Wankel engine and the generator combo power should not exceed the average power of a given load cycle if so, the size will increase.
2. The peak of the load cycle is 50 [kW] therefore the motor peak power capacity should not be of 50 [kWh] for an excavator.
3. The battery pack capacity is restricted to 30 [kWh] with a minimum 20% SOC (State of Charge).
4. The software used for this project will be 'AMESim'.

5. The major concern will be towards the sizing of Wankel engine, generator and additional auxiliary components for the range extender.
6. This project will stick to the configuration of 'Series Hybrid Electric Drivetrain' only.

1.6 Literature survey

An extensive study was done by researching various research papers which helped us to find about the range extender and its auxiliary components for sizing of a Wankel engine and the generator. Moreover, it helped in conclude with a good control strategy to achieve the driveline work for the load cycle provided.

Cole, D. E. (1972) this paper has a theoretical and historical information about the Wankel engine. Although the exhaust from the Wankel engine contains slightly more unburned hydrocarbons than the exhaust from a piston engine, it contains less NOx. Exhaust clean-up devices respond more favourably to the Wankel's operating conditions. This factor, together with the potential for reducing the size and weight of a vehicle built around the Wankel, makes the engine a strong candidate as a "clean" power plant. It was very important to improve our knowledge over the Wankel engine and its design and how does it work.

Mulugeta Gebrehiwot, Alex Van den Bossche, conducts research on Electric Vehicle possibilities using Low Power and Light Weight Range Extenders and making it carbon neutral to a larger extent. It shows the disadvantages for the electric vehicle and its limited range and proposed in adding the range extender to solve this problem. In this paper, a series hybrid electric vehicle configuration was used with the Internal Combustion Engine (ICE) as a prime mover which is coupled to the generator, and an electric motor to provide movement to the vehicle. This system can run with a small engine output in a stable operation efficiency region, supplying and generating electricity to the traction motor being sufficient for the average consumption. This allows a reduction of fuel consumption and a better sizing for the engine. This paper gave us a clear idea about the range extender components and how to minimize the range extender to get less size and weight.

Turner, the major goal of this paper is to analyze the 4-stroke reciprocating engine and Wankel engine as a range extender due to current battery technology limitations and to estimate the fuel consumption within a defined drive cycle. In this paper, two different range extenders were considered; a single rotor Wankel rotary and a 4-stroke reciprocating engine, with the baseline vehicle electric glider mass fixed for all options. In this paper, two different range extenders were considered; a single rotor Wankel engine and a 4-stroke reciprocating engine, with the baseline vehicle electric glider mass fixed for all options. After this, baseline Electric Vehicle performance was evaluated on simulated European drive cycles with mass sensitivity conducted before the implementation of each range extender. This paper explained to us the sensitivity analysis on mass and estimation of fuel consumption and gave the Potential options for the optimization of the range extender operation to be considered with respect to their impact on vehicle performance.

Ehsani, as we know that Electric and Hybrid Electric vehicles are now becoming well-known products in the market and are accepted internationally. However, their full potential for penetrating the automobile market is not yet fulfilled, even with the ever-expanding awareness of the global warming problem due to fossil fuel use. The abundance of hydrocarbon fuels is not going the change for decades and perhaps for centuries. Therefore, the electric and hybrid electric vehicles will dominate the automobile market only if they provide better and more appropriate products for the present and future needs of the automobile user. This book is an introduction to automotive technology and was very helpful it gave a complete idea about the hybrid vehicle and design the driveline and control strategy.

Mustafa Ozcanli, investigated the usage of Hydrogen as a fuel in the Rotary engines. This study focused on how hydrogen can be additional fuel for Wankel Engines. Hydrogen utilization in the reciprocating engine has shown that the Wankel engine is more promising and suitable for hydrogen enrichment. Because of the wide flammability limits of hydrogen, lean operating conditions of the rotary engine can be extended. So, the hydrogen existence can make a remarkable improvement in emissions and performance parameter. From this paper, one can focus on how or which types of fuels can be used for the Wankel engine and how hydrogen could be one of the options which can be preferred.

1 Sizing

1.1 Approach

1. *Calculating power needed by ICE, using the load cycle.*
   The average power of the given load cycle can be calculated by finding the total area under the curve and dividing it by the total time taken for 1 cycle to finish. This average power gives an estimation of the minimum power that the range extender must provide. Depending upon the peak power requirement and its duration, the minimum power that a range extender must deliver will be identified and similarly, the SOC levels at which the battery will recharge, and discharge will be finalized during the project implementing phase.
2. *Have an average line working on efficiency point (optimal bsfc)*
   There are two ways in which we can extract the required power from the engine using the graph of engine torque vs engine speed:
   i. By considering maximum power output.
   ii. By considering maximum fuel efficiency.

The former provides the maximum power but the downside to it is the excessive fuel consumption and the emission rates, which isn't the motive of this project. Furthermore, the majority of the power during the peak load will be given to the electric motor through the battery, therefore it doesn't give any perception to use the maximum power from the range extender. Hence for the same and the opposite reason, the latter is considered and will be implemented.

Once the power output of the engine and the generator is calculated, sizing estimation was calculated to various components. In the hybrid electric mode, the generator takes mechanical power. The power of the engine is given by:

$$P_{ICE} = T \times N \times (2\pi/60)$$

Where, $T = torque\ of\ the\ engine\ [Nm]$,

$N = angular\ speed\ of\ the\ engine\ [rad/sec]$

The generator is sized based on the ICE power rating, which is given by:

$$P_{Gen} = \eta_{Gen} \times P_{ICE}$$

With this estimation, the Wankel engine + generator combination should produce in the range of 25-30 [kW]. The difference load will be supplied by the battery.

3. The size of the Wankel engine is needed to supply enough torque/power for the battery to produce the given load.

1.2 Power calculation

The load cycle and the battery capacity were provided by the customer. In order to know the size of the Wankel engine an estimate for the average power consumption is calculated:

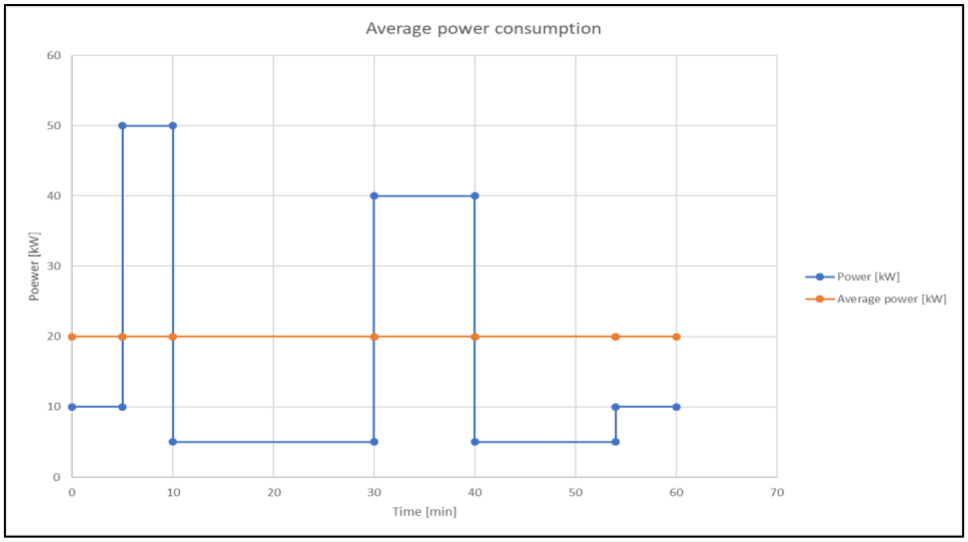


Figure 2- Average power consumption with the given load

Average power for given load cycle to be found out, which is 20 [kW] can be noticed from Figure 2. With the efficiency losses and optimum bsfc point the 225CS (30 [kW]) Wankel engine is good and light enough.

BSFC optimum around 292 [g/kWh] ---> 6000-8000 [rpm] range although on lower BMEP values (8.2-9 [bar]) in the shown Figure 3.

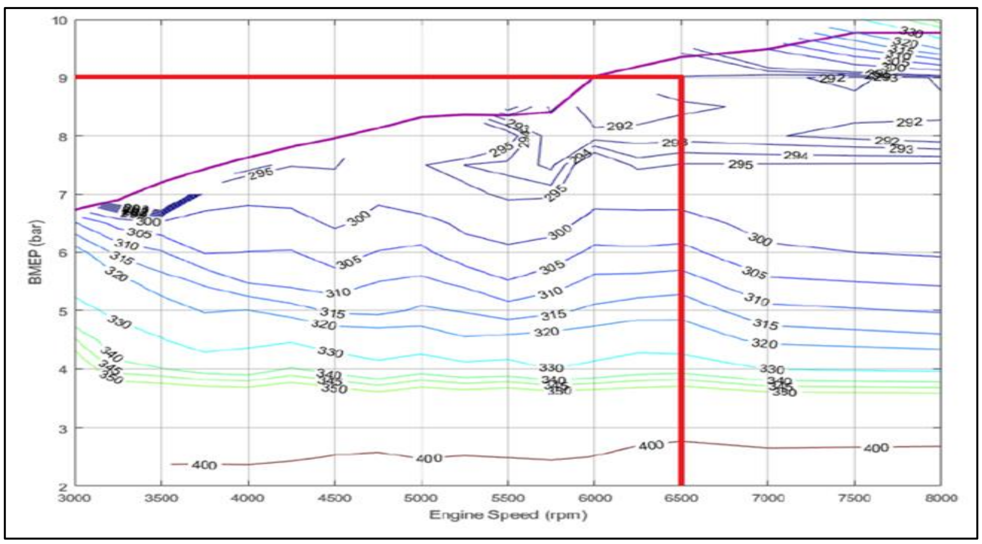


Figure 3- BSFC (g/kWh) map for 225CS Wankel engine (Turner, 2019)

At the optimum rpm range (for the BSFC) around 25 [kW] of power can be produced. Torque around that point is 36 [Nm]. As per the Figure 4 below.

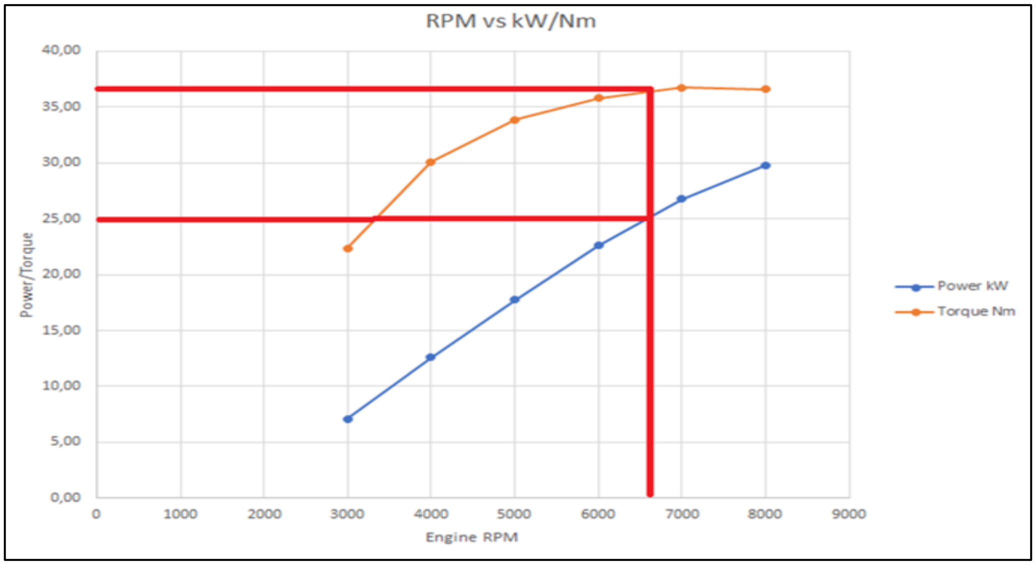


Figure 4- Power [kWh] and Torque [Nm] in the rpm range with optimum BSFC (Engineering)

To comply with the required power output from the given load case, at least 20 [kW] should be provided by the electric generator. That means with efficiency losses between the Wankel engine and motor-generator combo that a search for a 25-30 [kW] electric motor is made.

To check the possibility of a 25-30 [kW] electric motor a basic formula has been used. For this formula the torque output and the engine rpm have been used.

$$P = \frac{T*n}{9.549} = \frac{36*6600}{9.549} = 24.9\ [kW]\ \text{(toolbox)}$$

Torque maxes out around 37 [Nm] at 7000 [rpm]. This should be sufficient to supply the peak power in combination with the 30 [kWh] battery.

Electric motors around 36-37 [Nm] of torque are hard to find. However, a 30 [kW] with a max speed of 8000 [rpm] has been found and it has an added advantage, and the reason is for same 30 [kW] power generator it does contain higher torque. The torque curve doesn’t really follow the ideal path. This motor-generator gives however a good insight in the size.

1.3 Dimensions and Weight

Immediately after sizing, the required components which were mentioned in the previous chapter, based upon calculations, an exact or similar specification component which is already available in the market is searched on the internet and the dimension are as follows.

Size (Wankel Engine):

The Wankel engine 25CS–40BHP, developed by ‘Advanced Innovative Engineering’ delivers 30 [kW] of power. The figure below gives the dimensions of the core engine. (Engineering)

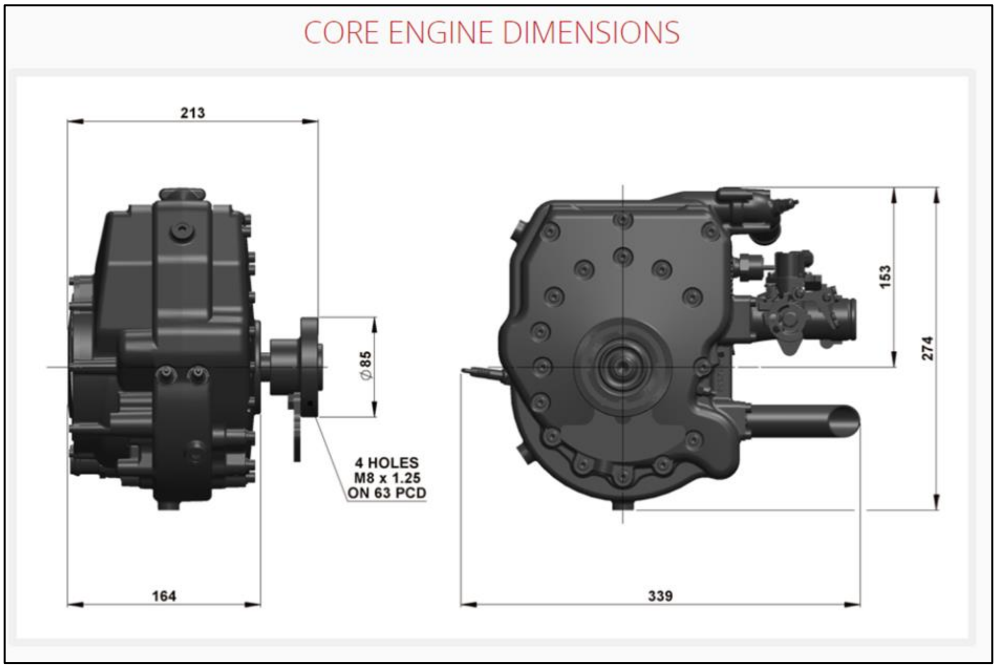


Figure 5- Core engine dimensions of the 225CS-017 rotary engine (Engineering)

The website or the additional document only shows the weight and not the size of these auxiliary components. Therefore, the extra size is roughly the size of the engine itself. So, core sizes are multiplied by two. The dimensions for the engine will be of rough estimation:

$$Length * Width * Height = 678 * 426 * 548\ [mm]$$

Motor Generator:

The electric motor/generator that was found on the internet is from a company called EV-Europe. The generator delivers rated power of 30 [kW], has a maximum speed of 8000rpm and churns out a maximum torque of 110 [Nm]. (Europe)

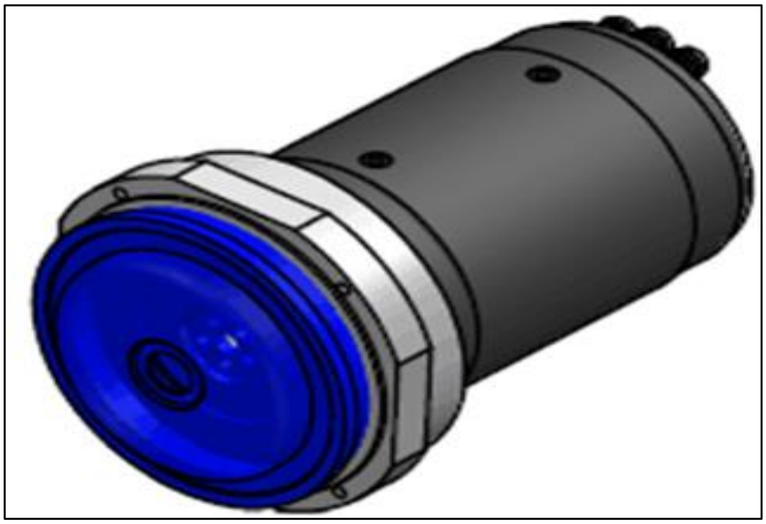


Figure 6- 50 AC electric motor (Europe)

The dimensions specified for the respective AC motor/generator:

$$Length * Diameter = 387 * 260\ [mm]$$

Total Dimensions:

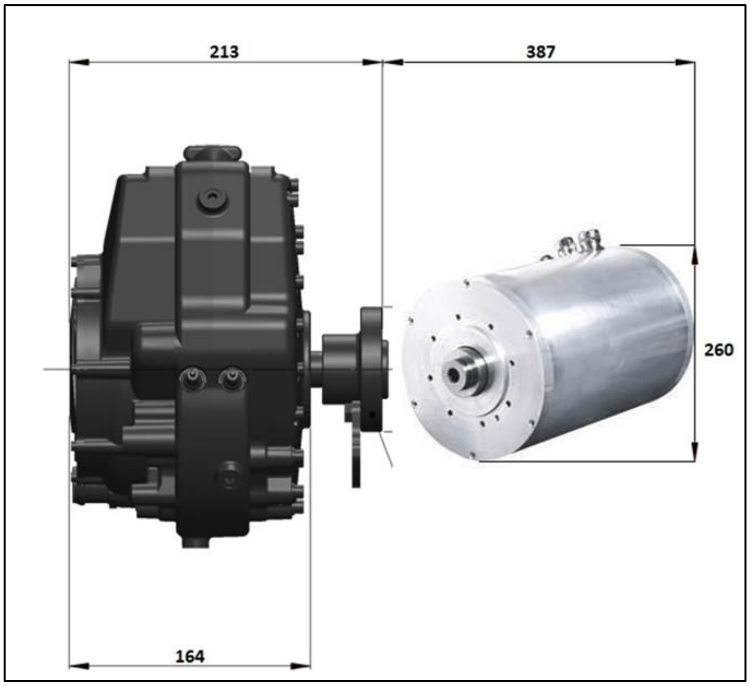


Figure 7- Graphical representation about the sizing of the range extender (Europe) (Engineering)

Summing up the sizes together (with some estimation for auxiliary components):

$$Length * Width * Height = 678 * 813 * 548\ [mm]$$

$$Volume = Length * Width * Height$$

$$V = 678 * 813 * 548 = 0.30\ [\ m^3]$$

The overall size of the range extender is around 0.3 [m^3].

1.4 Weight

Wankel engine

- Dry Weight 21.2 [kg]
- Core Weight 10 [kg]

Motor-generator

- Weight 59 [kg]

Combining the weights:

$$Total\ weight = 21.2 + 59 = 80.2\ [kg]$$

1.5 Packaging:

Packaging involves taking the dimension and weight into consideration. The components which are necessary for the engine/driveline to function are assembled together in the smallest possible volume. Figure 8 shows all the essential components assembled as a single unit.

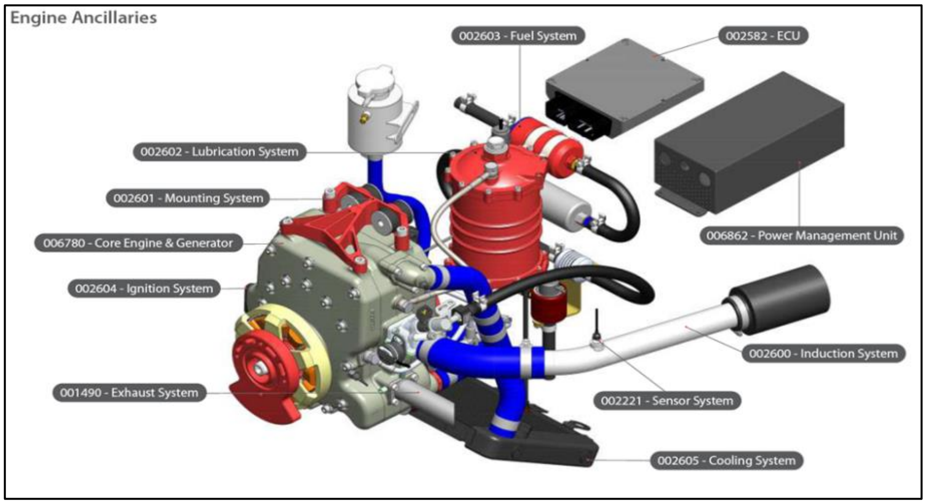


Figure 8- Wankel engine including auxiliary components (Engineering)

The table below shows the overall packaging of the engine and its auxiliaries:

Table 1- Packaging parameters

Serial number	Component name	Dimensions [mm]	Weight [kg's]
1	Core engine	$678 \times 426 \times 548$	10
Sub-components of the core engine			
001490	Exhaust system		0.11
002221	Sensor system		0.25
002582	ECU		0.38
002600	Induction system		0.64
002601	Mounting system		0.66
002602	Lubrication system		1.78
002604	Ignition system		0.34
002605	Cooling system		2.40
Electric motor/generator			
2	Generator	$387 \times 260\emptyset$	59
Vehicle's electric battery			
4	Battery	$198 \times 81 \times 425$	18.7 (filled)
Fuel tank			
002603	Fuel system		1.29
5	Fuel tank	615 x 455 x 290	81

Additional gearing maybe installed to transmit only the required power from the engine to the motor. The overall dry weight of the range extender is estimated at 100 [kg]. The weight of the core engine and its auxiliaries will be discussed in brief in the packaging section in this report.

The above-mentioned dimensions are an exception for electric motor/generator, strictly follows length width and height format.

Considering the excavator runs for 1 whole cycle continuously and each cycle consumes 4362 grams (4.362kg). Hence for 10 cycles, assuming that the excavator consumes the same amount of fuel in all the 10 cycles, the total fuel consumed would be 43620 grams (43.62kg). This kind of fuel consumption is ordinary in real world scenarios. Hence a 45kg capacity fuel tank is considered.

2 Fuels

The Wankel engine has been developed to run on all kinds of fuel but the most common fuel used in Wankel engine is gasoline. In this section, we will glance through various kinds of fuels which can be used in the rotary engine. As our goal is to reduce carbon emissions therefore fuels which are best is considered here. The following Table 2 shows the Netherlands fuels and standard CO2 factors for some kind of fuel. (Vreuls)

Main group IPCC (supplemented)	Unit	Heating value (MJ/unit)	CO_2 EF (kg/GJ)
A. Liquid Fossil, Primary Fuels			
Natural Gas Liquids	Kg	44.0	63.1
Liquid Fossil, Secondary Fuels/ Products			
LPG	Kg	45.2	66.7
Gas/ Diesel oil	Kg	42.7	74.3
Ethane	Kg	45.2	61.6
Refinery Gas	kg	45.2	66.7
Chemical Waste Gas	kg	45.2	66.7
C. Gaseous Fossil Fuels			
Natural Gas (dry)	$[Nm]^3$ ae	31.65	56.1
Methane	$[Nm]^3$	35.9	54.9
Hydrogen	$[Nm]^3$	10.8	0.0

Table 2- The Netherlands fuels and standard CO2 emission factors (Vreuls)

Hydrogen: Various studies about hydrogen enrichment have been focused on improvement for the combustion of Wankel type rotary engine. Hydrogen utilization in the rotary engine has shown that it is more promising and suitable. The wide flammability limits of hydrogen, lean operating conditions of the rotary engine can be extended. So, hydrogen existence can make a remarkable improvement in emissions and performance parameters.

Although usage of hydrogen can have a lot of admirable benefits, it's not outright preferable, especially not at all cheap. One of the major properties of hydrogen is that it has a very low density. In fact, it is less dense than any major fuels used right now. Due to this, hydrogen must be compressed to a liquid state and stored in the same state at lower temperatures to guarantee its effectiveness and efficiency as an energy source. For all these reasons, its common use is far from feasible. Although, hydrogen can be used in a rotary engine alone or it can be blended with different fuels like gasoline (Mustafa Ozcanli, 2017).

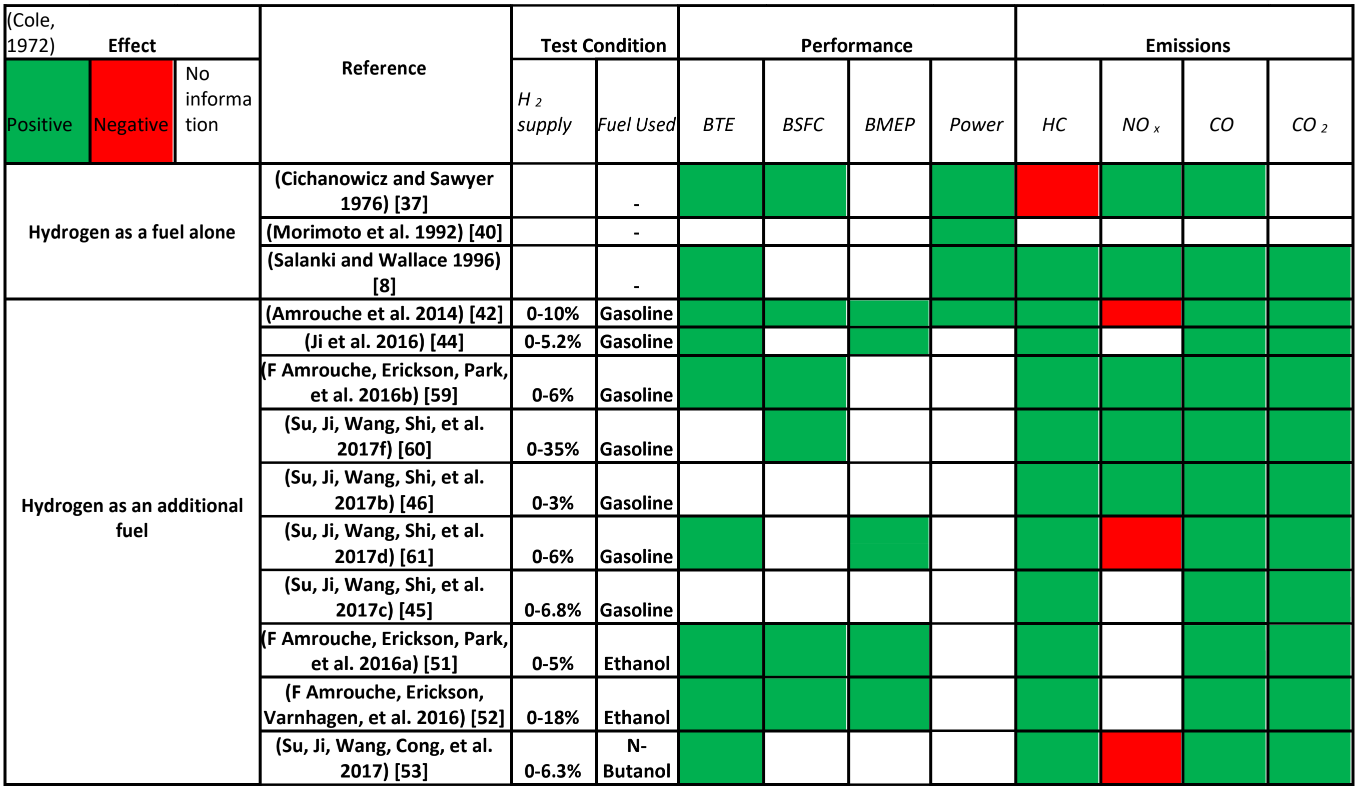


Figure 9- Summary of the experimental hydrogen usage studies in rotary engine (Mustafa Ozcanli, 2017)

LPG:

Liquefied petroleum gas (LPG) is a good alternative, as it is a better and cleaner burning fuel than diesel or petrol and also reduces the CO2 exhaust emissions by around 15% compared to petrol. The Netherlands has a good network for refueling of LPG all over the country and is much cheaper than other fuels. Although, LPG is a good option, there are some drawbacks while using it. The power produced while using LPG is 10% less than the power produced by petrol for the same engine size. Moreover, the ignition temperature is higher than that of petrol, therefore it reduces the lifespan of engine valves. Since the focus is on the sizing of the engine, the cylinders used to store LPG carries more weight which in turn increases the weight of an engine. The Table 3 shows the current prices of different fuels in The Netherlands.

Fuels	Prices
LPG	0.644 EUR/L
Unleaded	1.584 EUR/L
Diesel	1.261 EUR/L
Hydrogen	1.43 EUR/Kg

Table 3- Table of price kind of fuel in The Netherlands (Prices)

To conclude, recent studies have shown that The Netherlands is one of the most ambitious country looking forward for hydrogen as a fuel infrastructure initiative. As hydrogen fuel will cost us more and the storage capacity is also another issue, it's still one of the best options available with respect to carbon emissions. If we are looking for a cheaper alternative, we can suggest considering LPG or diesel as a main source of fuel for the engine. All the options have their own highlights and challenges and therefore it was necessary to understand what the main concern was while selecting the fuel whether it's the cost or the less emissions.

3 Modelling

The modelling for this project was accomplished using 'SIEMENS AMESim' software. This software assists in understanding various engine models and ensures a firm grasp on numerous classifications of powertrains models. The software also helps in including vehicle subsystems directly without the use of mathematical equations to design the hybrid driveline which was the core part of the project.

3.1 Engine Modelling

The library in AMESim software limits only to the use of conventional reciprocating internal combustion engine. Hence certain assumptions were made in order to realize the Wankel engine during modelling by utilizing the available conventional reciprocating internal combustion engine. The data imported to the software is of the Wankel engine by the means of "table creator". The engine files were generated based on the sizing which has been mentioned in the previous section. Then the obtained data files will be updated in DRVICE01H component to make it work as a Wankel engine. The Table 4 below shows the engine specifications that were used to realize the engine modelling.

1	Engine type	Rotary engine
2	Power output	30 [kW]
3	Stroke	90 [mm]
4	Peak torque	40 [Nm]
5	Engine speed	6000-8000 [rpm]

Table 4- Engine Specifications used in Engine Modelling

3.2 Motor/Generator Modelling

There are two courses of action to understand the modelling of the electric motor/generator. The first technique is through using a DRVEM02 component. Similar to the ICE, the DRVEM02 component has a choice for using "table creator". The data files can be produced based on the sizing of a generator which is discussed in the previous section. The obtained data files will be uploaded in DRVEM02 component to make sure that the generator produces the required power as per calculated value. The second technique is through searching an electric motor/generator specification catalogue on the internet and depending on the values of power requirement, corresponding torque values will be considered. This procedure will be performed to all the different values of the power cycle. This gives a torque cycle with respect to time. The downside of using this technique is that the torque cycle will be inaccurate and will deviate from the required/expected result. The Table 5 below shows the electric motor/generator specifications that were used to realize the generator modelling.

1	Type	Generator
2	Rated power output	30 [kW]
3	Max peak torque	110 [Nm]
4	Max speed	8000 [rpm]
5	Controller voltage	96 [V]

Table 5- Motor/Generator Specifications for modelling

3.3 Driveline Design

As per the customer requirement, the given driveline will be of series-hybrid transmission. It uses two power sources linked together, with only one source directly connected to the vehicle's transmission. The Wankel engine is used to power the generator that converts the mechanical energy to electric energy. Then providing the electric power to the vehicle's battery and the electric battery supplies the required power for hydraulic motor components to perform digging activity as well as to the traction motor to drive the excavator. The assumption has been made that a single motor will perform both the activity of traction motor and hydraulic motor.

A series hybrid configuration uses two electric motor/generator. Since there is no mechanical connection between the engine and the drive wheels, there is no need for a transmission. This is an added advantage with reference to packaging since space is consumed only by the engine, generator and its respective auxiliaries. The below shown Figure 10 is the representation of a series hybrid vehicle.

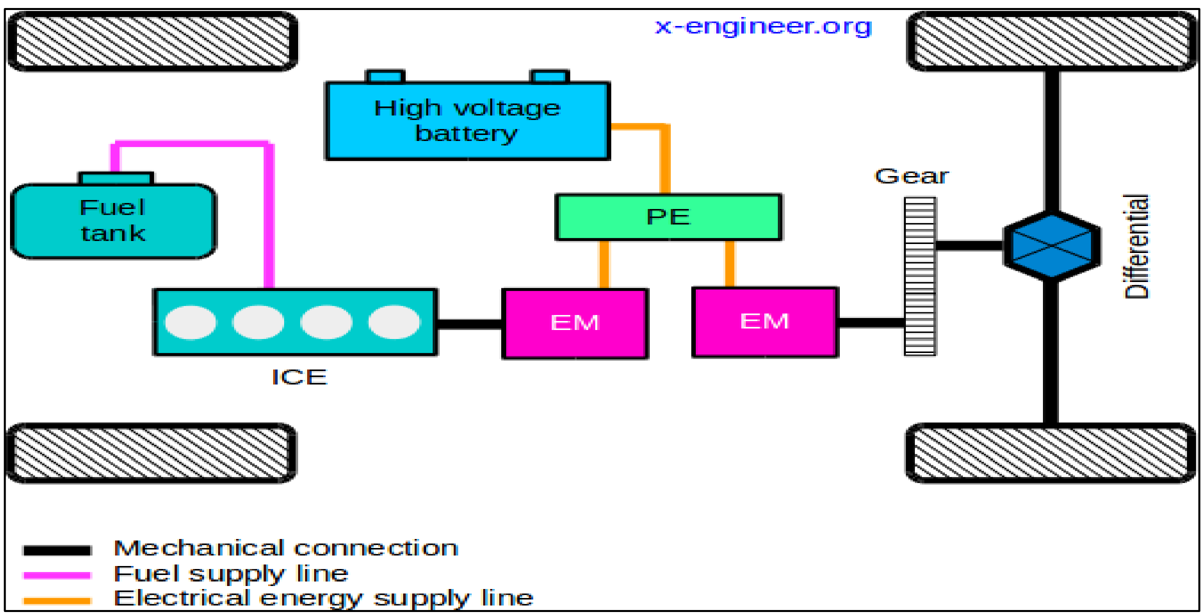


Figure 10: Series Hybrid Configuration (x-engineering, n.d.)

3.4 Battery

The battery package of 30 [kWh] was provided by the customer with a condition that the SOC shouldn't drop below 20%. AMESim offers various kind of batteries nonetheless, in this model DRVBAT001_SENSED component is utilized. The Table 6 below shows the vehicle's battery specifications that were used to realize the battery modelling.

1	Battery voltage	500 [V]
2	Rated capacity	75 [Ah]
3	Initial SOC	75 [%]
4	Battery energy	30 [kWh]

Table 6- Battery Specifications for Battery Modelling

3.5 Implementing Load Cycle

Succeeding the various component designs through different library tree available in AMESim software, the given power load cycle was bifurcated into two separate cycles of torque and the angular speed with respect to time. The purpose of following this technique owes to the fact that we cannot feed the given power cycle directly to the motor.

The splitting of power will be carried out after obtaining the values from table creator and will be fed into the motor. Once the load cycle is provided to motor the obtained output power will be checked using a power sensor to verify that power obtained is same or not. Figure 11 shows the given load cycle.

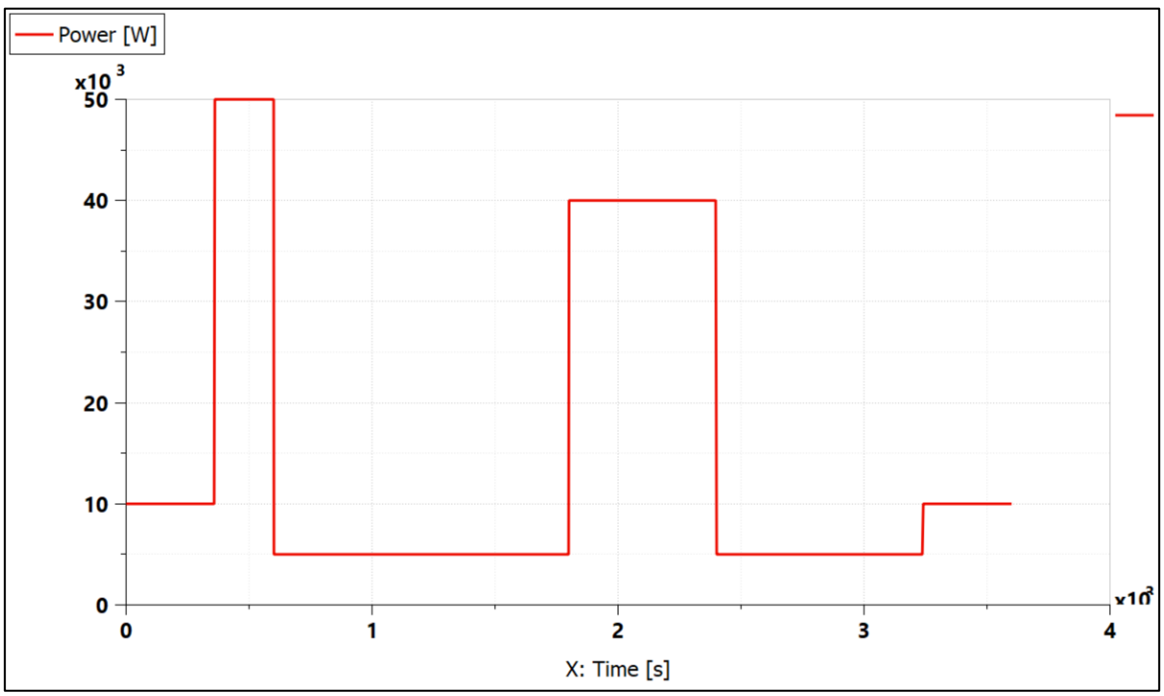


Figure 11: Given load cycle.

3.6 Control strategy

Control strategy for electric vehicle charging and discharging had been carried out by controlling the combustion process of the engine and was implemented using SOC on/off strategy. The setpoint for the initial SOC of the battery was at 75%. Commands were given in such a way that the SOC should not drop below 40% (SOC on) and the engine had to shut down at 75% (SOC off). These points control the working operation of the engine.

Power was calculated by multiplying the current flow to the motor with the battery voltage. For the speed control, we converted the obtained power to angular speed and dividing it with the maximum torque of the engine. Furthermore, we need to control the angular speed signal of a generator in such a way that it will not exceed its max speed using proportional controller. Depending upon the combustion process, the motor was controlled using a switch. The obtained output, angular speed is fed to the motor/generator. For the torque control, we divided the power obtained from the battery with the angular speed to procure the torque, which will be fed as an input to the engine. Before feeding, we found the ratio between the calculated torque and the maximum torque. The signal will be sent to saturation before sending to the ECU as it will be giving a command in binary signal. This is also governed by the combustion signal coming from the on-off strategy.

4 Noise Vibration Harshness (NVH)

One of the major considerations in the current scenarios is the NVH levels of the machine/vehicles. Manufacturers are showing more concerns in reducing the NVH levels of their products which can cause distress to other people or to the driver itself. Loud noise coming from the vehicle will cause irritation to the neighbors and the high noise and vibrations will cause fatigue to the driver. The major components that create loud noise and harsh vibrations are the engine, transmissions, the motor-generator and other auxiliary components. The Table 7 below shows the threshold decibel levels that any human can sustain over a certain period of time. The table shows how long a person can tolerate certain different level of decibels.

	Duration	Sound level [dB]
Hours	24	80
	8	85
	2	91
	1	94
Minutes	30	97
	15	100

Table 7- Toleration levels at different sound decibels (solution, n.d.)

Long encounter to noise levels in excess of 85 decibels will result towards permanent hearing losses and experiencing harsh vibration above 4 [Hz] for longer periods of time will cause nausea and several other complications to the body. Hence it is an utmost necessity to reduce NVH levels.

Counterbalancing NVH boils down to three essential standards – diminishing it at the source, secluding it from the vehicle's fundamental construction and retaining as much as possible before it enters the cabin. Various ways of reducing NVH in certain components are listed below.

4.1 Engine:

- Noise and vibrations generating from the engine can be reduced by using vibration dampers or rubber mounts to secure the engine firmly to the chassis. (Bankbazaar, n.d.)
- Engine covers can be used which dampens the sound coming from the engine while the outer part of the cover will help in reduction of heat buildup. Additional sound dampening foams can also be installed around the engine.
- By completely covering the engine, by securing it in a separate chamber and insulating the chamber walls with sound damping materials will reduce the noise.

4.2 Motor:

- One of the easiest and the most effective way to reduce motor noise is through connecting a capacitor to one end of the motor terminals.
- Motor lines can induce current in neighboring wires as well. So, by keeping a separate line of the motor connection will help in reducing the noise.
- Reduction of the number of resonances occurring between electromagnetic excitations and structural modes. (guide, n.d.)

4.3 Auxiliary components:

- Noise from the radiator fan can be reduced by minimizing its rpm for a certain amount of air flow.
- Fuel tanks are large components that can produce a lot of NVH issues if not engineered well. A common way fuel tank manufacturer combat NVH is by using rubber pads that are positioned between the fuel tank and the cars body.
- Utilizing mufflers inside the silencer will reduce the sound coming from the engine drastically.

Inside the engine bay installing an *'active noise cancellation' unit* could also be considered as an option. It operates by conveying a sound wave at the specific inverse period of the engine noise. At the point when the two waves locate one another, they counterbalance each other and results in silent cruise. Yet, the drawback of this is that the engine does not always produce the same amplitude and frequency of sound. (guide, n.d.)

5 Results

This chapter analyses the results obtained during the simulation. Parameters were imported to the model based on the calculations performed during the sizing phase. Several dominant graphs have been plotted and the discussion is based on these graphs.

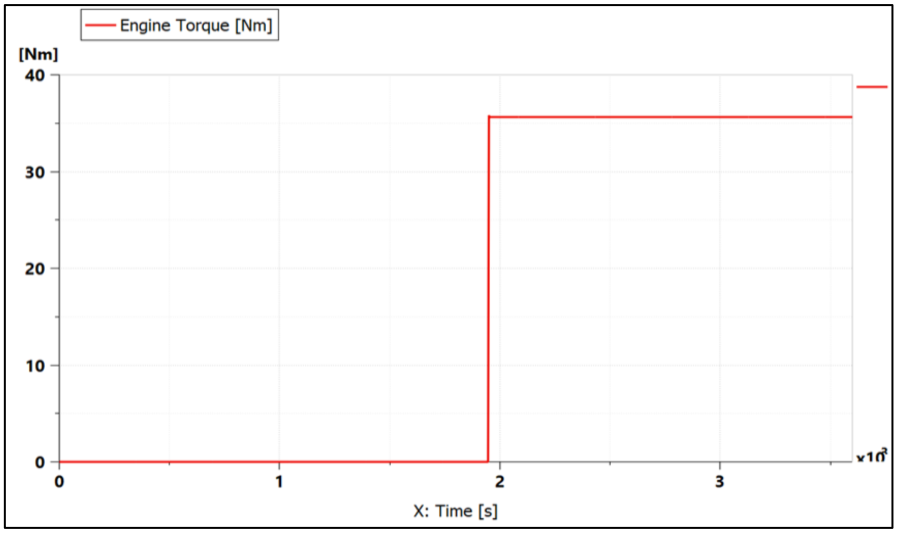


Figure 12- Engine Torque with respect to Time

Figure 12 represents time vs engine torque. Although the peak torque of the engine is 40 [Nm], the amount of torque that is obtained is around 36 [Nm] this is due to the fact that the engine operates at 90% efficiency and has been set in the control strategy. Moreover, it is sufficient to deliver the power required by the electric motor/generator. Provisions can be made to increase the torque of the engine to its peak value, which would lead to faster charging of the Peak Power Source (PPS). Nonetheless, the fuel consumption would certainly increase which would moderately deviate the objective of this project.

Figure 13 shows the peak engine speed (8000 [rpm]) corresponding to the peak engine torque of 40 [Nm]. As it is mentioned earlier that the engine torque can be controlled but not the speed hence in the graph it is visible that the engine is running at max speed.

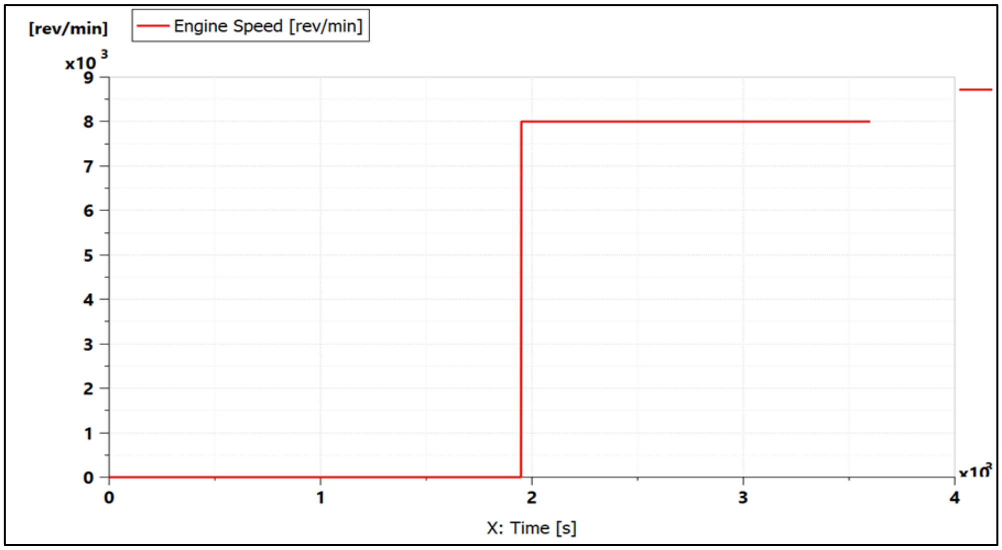


Figure 13-Engine Speed with respect to Time

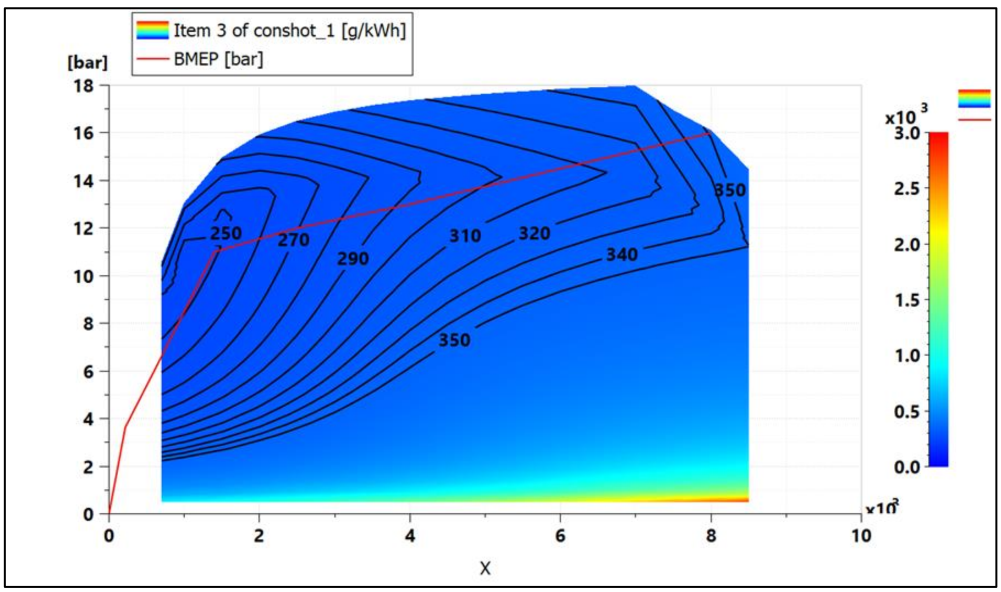


Figure 14- The BMEP Graph of the Engine

Figure 14 shows the generated BMEP Graph of a Wankel engine. In the real-world scenario, the minimum fuel consumption usually falls in the mid-range rpm. The Wankel engine properties were updated for a normal ICE engine component and it can be observed from that minimum fuel consumption region is at a lower rpm in the graph. This is due to non-availability of Wankel engine component in AMESim library.

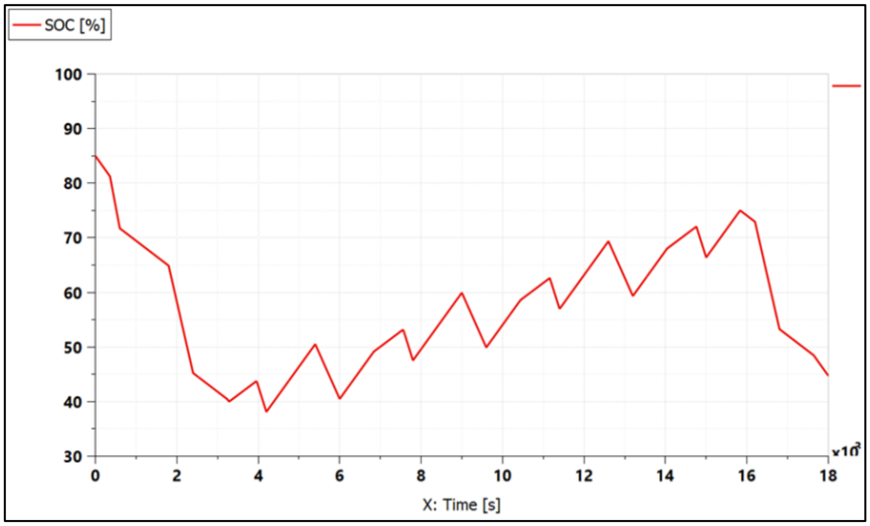


Figure 15- Battery's State of Charge over Time

Figure 15 depicts the graph for the 'State of Charge' (SOC) of the battery which was simulated for five power load cycles (18000 seconds). The on-off strategy command was stated to work from 40% to 75% SOC. Once the SOC of the battery hits its lower threshold value of 40 %, the range extender kicks in and runs the electric motor/generator which in-turn recharges the battery. The battery recharges until the 75 % of the battery SOC is achieved, promptly reaching the desired SOC the Wankel engine shuts down and the power to the motor is supplied solely by the battery.

As perceived from the graph, there is an ascending trend of continuous charging and discharging of the battery SOC. This is due to the fact that due to the high load requirement at that particular moment, the battery has to spend its extra energy to overcome the load. Hence there is a discharging phase in the battery whereas it is the exact opposite of what is happening during the charging phase. Owing to the larger idle and driving time, the power produced by the engine is abundant to charge the battery for longer durations of time.

6 Fuel Consumption Estimation

Fuel consumption estimation can also be done by using AMESim software. A standard Dutch working week is 38 hours. The majority of fulltime jobs in The Netherlands are between 36-40 hours a week, or seven to eight hours a day, five days a week(IamExpat Media). Considering 8 hours a day for the estimation of the fuel consumption. For 8 hours the SOC graphs will be plotted. The total fuel consumption graph will be checked for the fuel consumed.

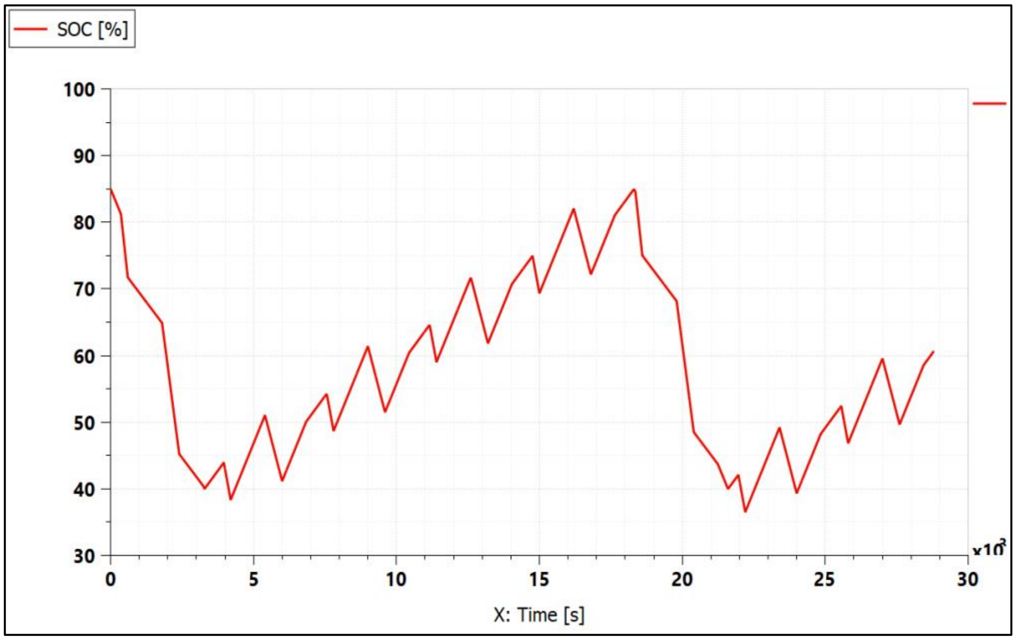


Figure 16: SOC graph for 8 hours load cycle

From Figure 16 it can be seen that engine is made to operate at best SOC economical region.

From AMESim:

The total fuel consumption of the Wankel engine for 8 hours from Figure 17 is

$$64755\ [g] \approx 64.75[kg] \approx 64.75[l].$$

For 1-hour total fuel consumption will be:

$$\left(\frac{64.75}{8}\right) = 8.09 \approx 8.1\ [l/h]$$

Hand calculation:

The total fuel consumption is given by the formula:

$$Fuel\ consumption = \frac{Specific\ fuel\ consumption * power}{Fuel\ specific\ weight}$$

The graph plotted for the BMEP in Figure 14, shows us that the optimal fuel efficiency region is around 250 $[g/kWh]$, the peak power originating from the engine is 30 [kW] and the specific fuel weight (density) is considered to be $730.941 kg/m^3$.

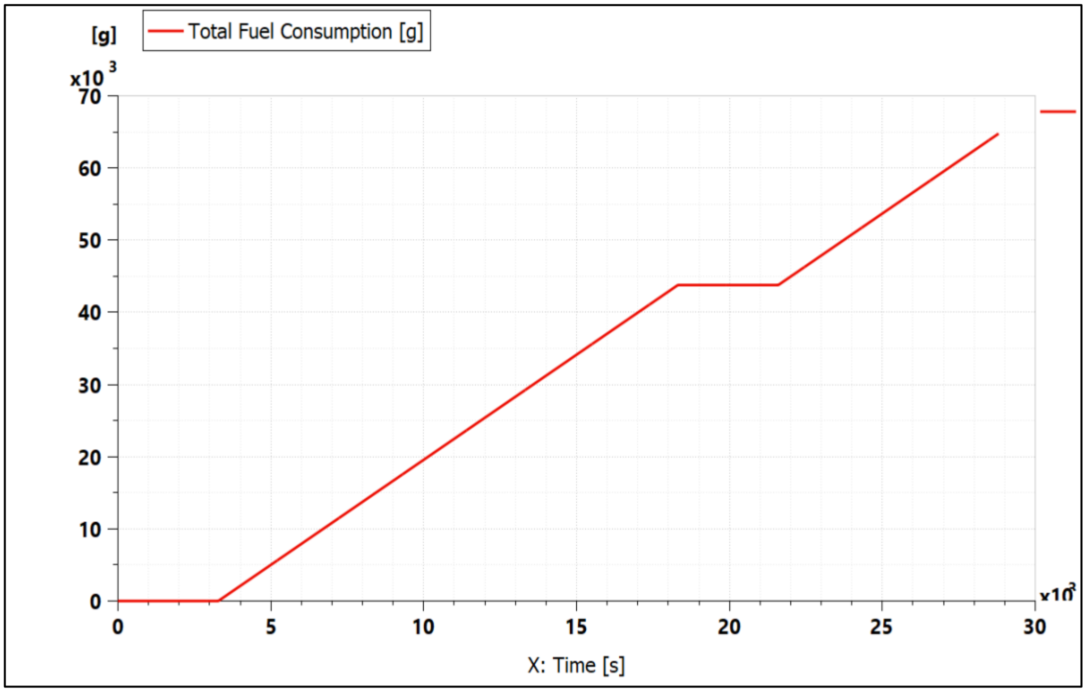


Figure 17: Total fuel consumption for 8 hours load cycle

Using the above formula, we can calculate the total fuel consumption.

$$Fuel\ consumption = \frac{250\ [g/kWh]\ * 30\ [kW]}{730.941\ \ [kg/m^3]} = 10.26\ [l/h]$$

The difference between AMESim model and hand calculation values is $= 10.26 - 8.1 = 2.16[l/h]$. The reason for the hand calculation value being higher than the result obtained in the simulation, is because the formula considers the engine to be operating all the time. Whereas, in the AMESim model a genuine control strategy has been administered and it opts for the optimal plan of action, based on the load conditions.

The second calculation is based on the assumption that the engine is operating away from the sweet spot and at much higher specific fuel consumption value in BMEP graph in Figure 14. From the same figure, maximum fuel efficiency region is perceived to work around 350 $[g/kWh]$. Considering the constants such as peak power from the engine to be 30 [kW] and the specific fuel weight to be 730.941 $[kg/m^3]$. Utilizing the same formula, we obtain a new fuel consumption to be:

$$Fuel\ consumption = \frac{350[g/kWh] * 30\ [kW]}{730.941\ [kg/m^3]} = 14.36\ [l/h]$$

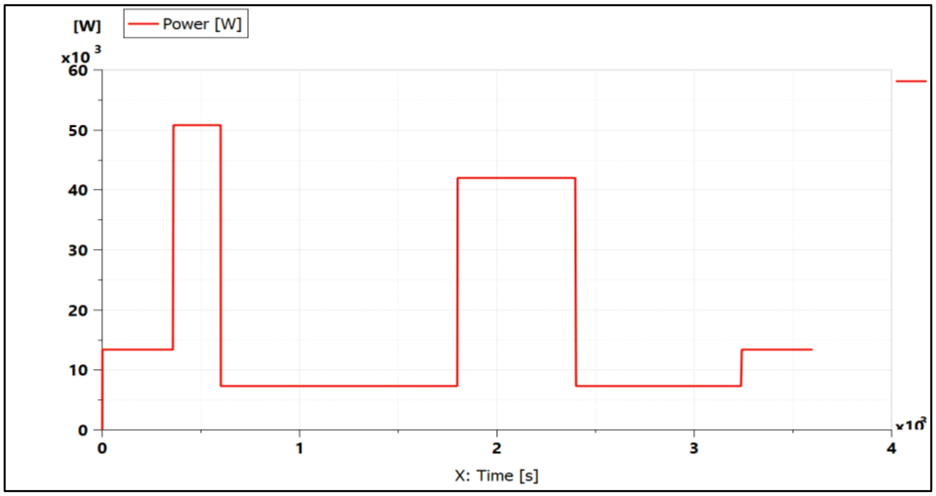
The difference between maximum specific fuel consumption and optimal specific fuel consumption is $= 14.36 - 10.26 = 4.1[l/h]$. This is a huge margin because the fuel being saved per hour is 4 liters and per day, it would sum up to 32 liters. This alone gives a huge motivation to utilize a range extended vehicles versus a conventional ICE vehicle. Apart from this, this considerably reduces the greenhouse emission gas.

7 Validation

7.1 AMESim model

To check the validity of the model, provided data should be able to predict and match the simulated results accordingly as per the given power requirement.

As power requirement is the main objective, the motor and the battery should be able to provide the required power in order to compete with the demand power.



(a)

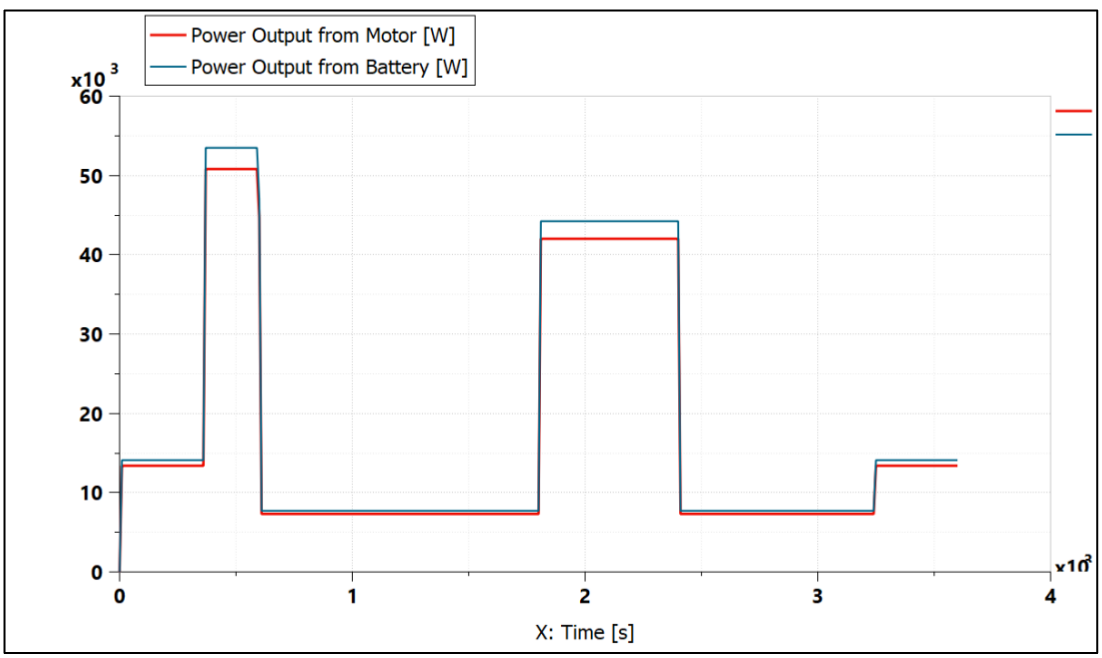


Figure 18: (a) Demand power vs time graph (b) Power output from the motor and battery respectively

Figure 18(a) displays the demanded power from the load cycle, whereas Figure 18(b) demonstrates the power output from both the motor and the battery discretely. The power output of the battery from the figure (b) is modestly higher than the required power, this is due to the motor efficiency of 0.95.

As per the sizing calculations, engine of 20 [kW] should be able to charge the battery during idling and driving mode. Below shown Figure 19 is able to power the battery and been compared with Figure 2 for a given load cycle.

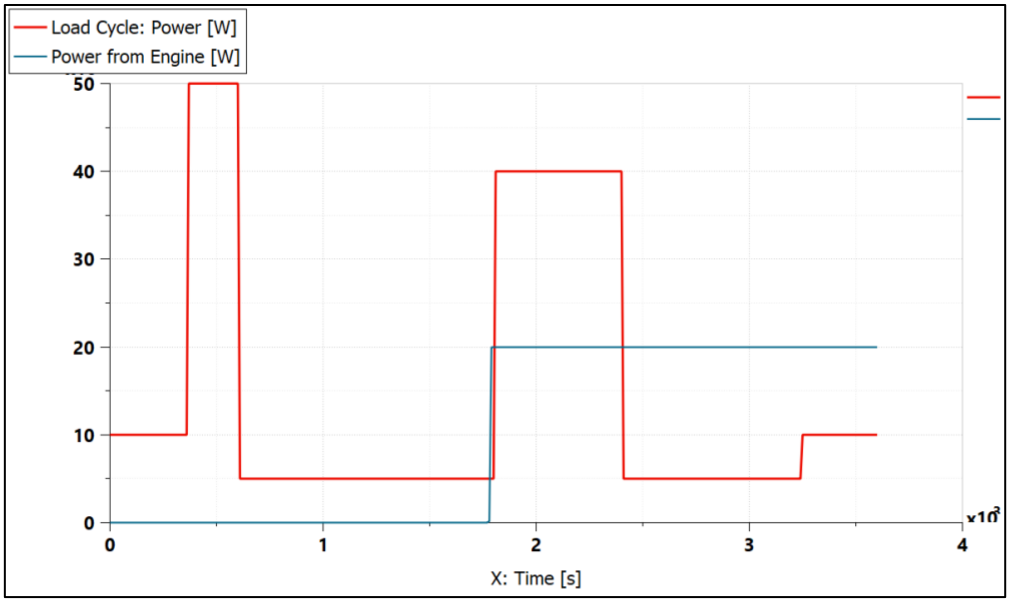


Figure 19: Engine power cycle compare to load cycle

Another approach is implemented through Hybrid Optimization Tool (HOT). Identical parameters were uploaded into the toolbox for all the components and the load cycle is carried out by giving inputs as an electric input whereas very negligible inputs are given to the speed data. This is done solely because the HOT model does not retrieve any sorts of errors. Once the model is executed, the graphs for BMEP of the engine, generator and motor operating points and SOC graphs are obtained and are discussed below by comparing against the primary model.

The primary model is compared with the HOT model. Out of both the model's, the engine operating points from the BMEP graphs appears to be around the optimal region. It can be observed that the engine is operating roughly around the 35-37[Nm] range which is truly close to the primary model, where the engine is operating at 36[Nm]. The Figure 20 shows us the Engine operating points from the HOT Model.

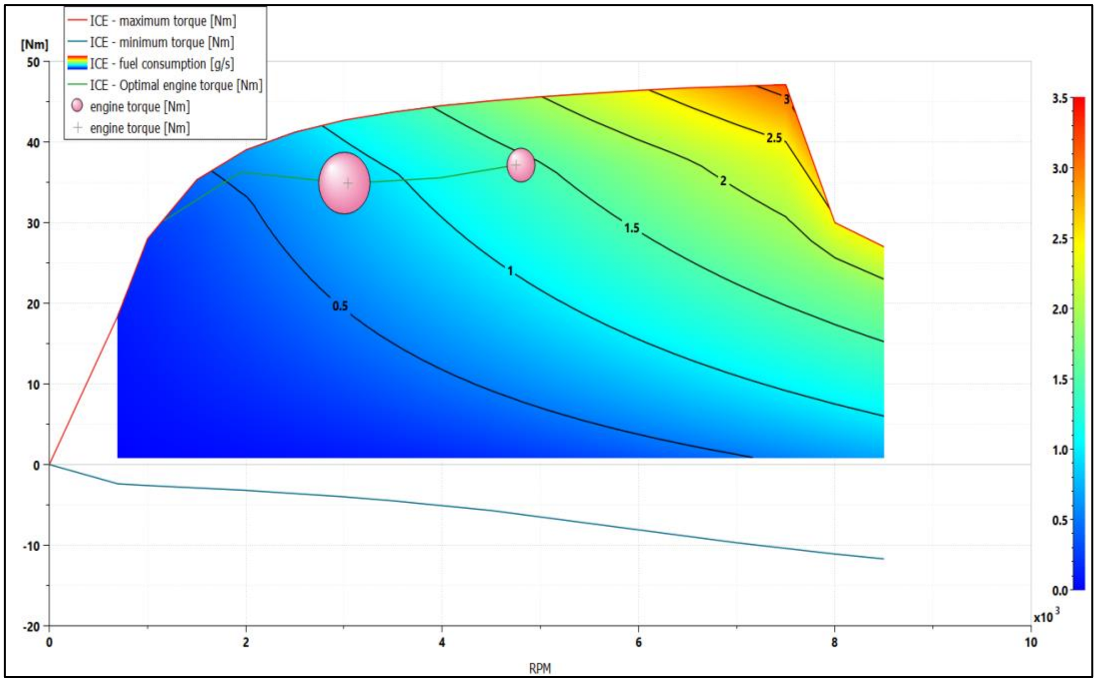


Figure 20: HOT modelling engine operating points

Similarly, the generator operating points obtained from the HOT model are in the span of 33-35[Nm] which is indeed matching with the primary model, as can be seen in the below Figure 21. The sole difference is that the minimum starting torque in HOT model is 50[Nm] as base speed conversely in the primary model the base speed is 60[Nm]. The reason behind this is because of the software algorithm, the HOT model continuously tries to optimize the give situation hence the software has considered the base speed as 50[Nm].

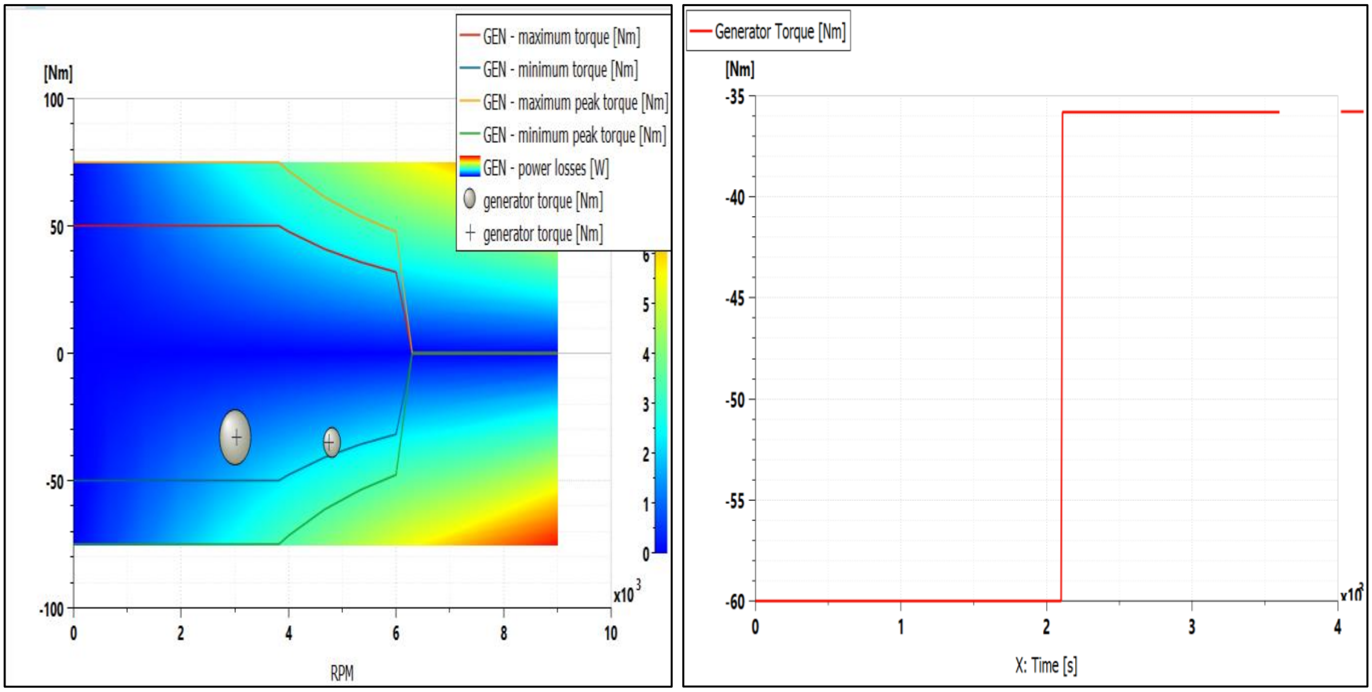
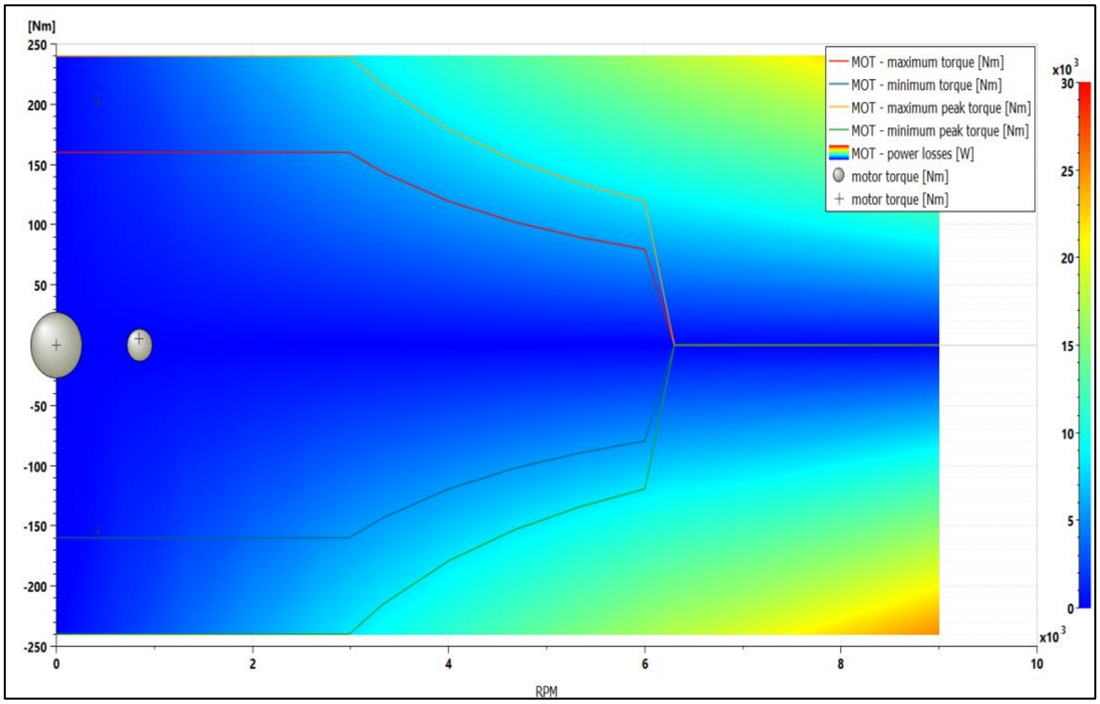


Figure 21: Comparison between HOT model and developed model generator torque graph

The motor and SOC graphs are plotted and shown in Figure 22 below.

The figure shows the motor operating points, as observed there are no operating points at higher rpm for the motor. This is because the user defined speed profile is negligible. There is a single motor operating point in the graph, which is because in the given load cycle, driving mode will activate only once at 10 [kW]. The velocity corresponding to 10 [kW] is found out to be 1.82 $[m/s]$. Due to the fact that the required load cycle is user defined as an electrical input, the HOT model is considering the electrical input as an auxiliary component. Hence majority of the power coming from the battery is consumed by the generator and providing it to the auxiliaries. This leads to charge depletion state of battery as the engine is failing to deliver the required power to charge the battery and it also does not have sufficient time to supply to battery. During this operation motor will not be working.



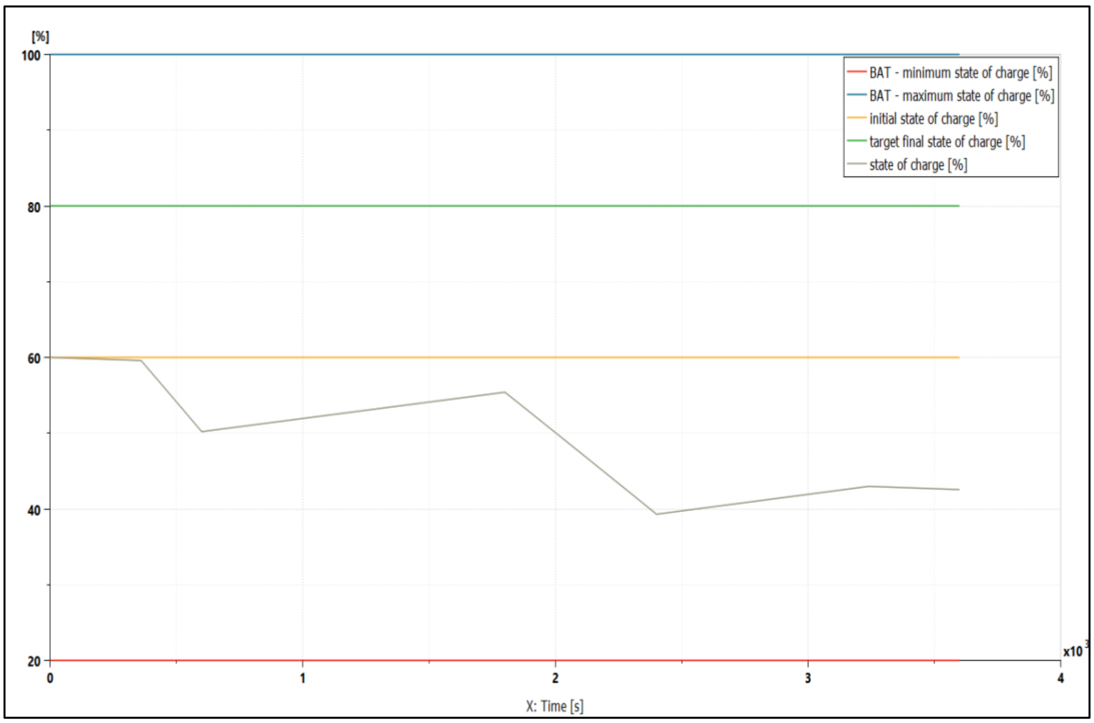


Figure 22: The motor operating points and SOC graphs for HOT modelling

7.2 Validation of calculated engine size

To see if the dimension and weight numbers make sense, a comparison must be made. A comparison is made with other existing 30 [kW] range extenders.

Parameters	Calculated	KSPG (Andert, 2012)	MAHLE (Bassett, 2013)
Length [mm]	678	665	327
Width [mm]	813	550	416
Height [mm]	548	355	481
Weight [kg]	100 (80)	62	70
Note	With estimation of auxiliary components	Basic module without add-on components	
Configuration	Wankel + 30 [kW] generator	2-Cyl, 4 Stroke SI + 2 x 15 [kW] generators	2-Cyl, 4 Stroke SI

Table 8- Calculated Dimensions and Dimensions from papers

As it can be seen in the Table 8 the calculated values are in the range of actual existing range extenders. Some parts are a bit wider or heavier than existing. This is because assumptions are made on the bigger side. Also, the KSPG range extender doesn't include "add-on" components. It also uses two 15 [kW] generators instead of one 30 [kW]. The biggest part of the weight in the calculated range extender is coming from the generator (~ 60 kg).

8 Discussion

8.1 Discussion of results

The primary AMESim model (and results) shows that a 30 [kW] Wankel engine-generator combination is sufficient as a range extender. Combining the power originating from the range extender along with the battery power, the power requirement can easily be met.

One may argue that a smaller range extender is the next best option. The Wankel engine is almost as small and light as possible. With a marginal gap to the peak power this engine could run at a lower bsfc and is therefore “greener”. With a lower fuel consumption there are less emissions, a smaller fuel tank is needed (or the range is increased) and the total “lump” mass the vehicle is carrying is less.

Limitations

The AMESim model gives an estimation on fuel consumption, but this is based on the BSFC map from a “normal” four stroke SI engine. For a Wankel engine the mapping is different therefore an accurate hand calculation has to be made. Fully recalculating will take a lot of time.

Another limitation is the assumptions made for the auxiliary components, as the specification sheet only mentions weight of the components and not the size.

Future research

For future research an accurate BSFC map for the Wankel engine should be implemented, so a precise fuel consumption and emissions estimation can be delivered. Apart from this, a lighter and more suitable generator can be found for a better overall performance of the range extender. Perhaps the results can be validated with other programs or calculations.

9 Conclusion and Recommendations

9.1 Conclusion

The objective of this project was to size a Wankel engine, generator and its additional auxiliary components, as a range extender according to the given load cycle and making it carbon neutral to a larger extent.

Following the stated approach, a size for the Wankel engine is achieved. The total range extender delivers 30 [kW] of power, has a volume roughly about 0.3 [m^3] and weighs less than 100 [kg]. To make it as green as possible the engine will try to run at the lowest fuel consumption. For the same reason, a small and light engine has been searched, as additional weight would increase the emissions.

In addition, a good control strategy was developed to satisfy the power requirements by making the driveline work at the optimal range for the load cycle.

For the control strategy, the Wankel engine will turn on if the battery SOC level is going below the given set point. The minimum of 20 % SOC will not be reached. Combining the battery with the engine and generator combination, gives sufficient power under the provided load cycle.

Hot modelling will give results only for engine and generator, this is due to the fact that HOT modelling considers electrical consumers as auxiliary components. Hence motor operation will not be obtained therefore, using HOT model we cannot design the desired objective but rather helps in better understanding.

9.2 Recommendations

Some recommendations have been stated under this section for future scope of work.

- Study can be done extensively on the fuel selection
- Auxiliary components were sized considering a rough estimation rather than a deep study of each component and how it affects the packaging. Auxiliary components can be studied, how they influence the packaging and size them accordingly to attain much better results.
- Various control strategies can be implemented, by defining the engine operating point at high, medium and low speeds based on the SOC level region.

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