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ORIGINAL ARTICLE

# Modelling an Electrically Turbocharged Engine and Predicting the Performance Under Steady-State Engine

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**ABSTRACT** – This paper discusses the evaluation of the energy recovery potential of turboshaft separated (decoupled) electric turbocharger and its boosting capability in a spark-ignition engine through simulation-based work and comparing it to a conventional turbocharged engine in terms of fuel consumption. The main objective of this study is to evaluate the amount of energy that can be recovered over a steady state full-load operating conditions and boosting capabilities from a decoupled electric turbocharger of an SI engine using a 1-D engine simulation software. The electric turbocharged system includes two motors and a battery pack to store the recovered electrical energy. Gt-Power engine simulation software was used to model both engines and utilizes each of the components described earlier. The conventional turbocharged engine is first simulated to obtain its performance characteristics. An electric turbocharger is then modelled by separating the turbine from the compressor. The turbine is connected to the generator and battery, whereas the compressor is connected to the motor. This electrically turbocharged engine was modelled at full load and controlled to produce the same brake power (kW) and brake torque (Nm) properties as the similarly sized conventional turbocharged engine. This step was necessary to investigate the effect an electrical turbocharger without a wastegate has on the engine's BSFC and determine the energy that can be recovered by the electrical boosting components, and cycle-averaged fuel consumption was evaluated. The evaluation of energy recovered from the electrically turbocharged engine from the analysis can assessed in full-load steady state conditions that can be useful for research in part-load and transient studies involving the decoupled electrical turbocharger. The study revealed that a maximum of 21.6 kW of electrical power can be recovered from the decoupled electrical turbocharger system, whereas 2.6% increase in fuel consumption can be observed at 5000 rpm engine speed.

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## INTRODUCTION

The necessity for an efficient and environmentally friendly engine has never been more profound than in recent times. Car manufacturers are made to comply with the most stringent emission standards imposed by the authorities. Carbon monoxide (CO) and nitrogen oxide (NOx) emissions are limited to 1 g/km and 0.08 g/km, respectively under Euro 6 requirements, while the carbon dioxide (CO2) emissions are limited to 98 g/km [1]. These legislations bring about new challenges for manufacturers to find new ways of lowering emissions and fuel consumption. Engine downsizing has become the mainstream solution for manufacturers to adhere to the legislation. Downsizing is the act of decreasing the volumetric capacity of an engine for reduced friction and throttling losses where the induction of the engine needs to be increased. The boosting can be done by using a turbocharger. A turbocharger compresses air at the intake manifold through the use of waste exhaust gases. Waste heat recovery has been a popular method for manufacturers to increase the volumetric efficiency of their engines [2]. The amount of air passing through the turbine determines the level of compression produced by the compressor. During operation, most of the exhaust gases are bypassed to avoid over-boost and over-speeding. Conventional turbochargers use a wastegate that bypasses the exhaust gasses from the turbine, thereby not fully exploiting the energy recovery potential of the boosting system [3].

Electric turbochargers can improve conventional turbochargers by eliminating or minimising their flaws. Although matters like the efficiency of both electrical machine and turbomachines need some addressing, electric turbo-compounding makes a compelling prospect in future vehicle applications due to its potential to lower BSFC [2]. Pavlos et al. [4] investigated the prospect of electric turbochargers to control load and whether they can replace a wastegate valve. While increasing the thermal efficiency of the engine causes it to produce up to 6.6kWh of energy, the incorporation of a motor generator also shortens the response time by up to 90%. By using a larger turbine, the wastegate can be inhibited, but this leads to worsening the engine's response time and to increased energy demand at low engine speeds. Wei et al. [5] did a study on the performance of three different types of electric turbochargers. The engine, turbochargers, and turbogenerator under US06 and FTP75 driving cycles were modelled in 1D simulation software. The findings were

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that, the electric turbocharger with a turbogenerator that is parallel with the turbocharger performed better than the other setups with better fuel economy of 4% under US06 driving cycle and 1.6% under FTP75 driving cycle. Mamdouh et al. [6] did a 1D simulation model consisting of electrically assisted turbochargers that was made to be used in the design of a turbocharger centrifugal compressor. A conventional and electrical turbocharger was also modelled for engine performance. The electrical turbocharged engine model was run at power levels between 1kW and 5kW based on the compressor design obtained from the electrically assisted turbocharger simulation. The engines' power levels with 1 kW and 5 kW electrical turbochargers increase by 5.96% and 15.4%, respectively. The 1 kW and 5 kW electrical turbocharger engine models produced a decrease in BSFC of 0.53% and 1.45% respectively.

Grujić et al. [7] tried to analyse the working parameters of the internal combustion engine with a hybrid turbocharger. The transient response of the turbocharger and exhaust gas volumetric flow to the turbine should be optimum to effectively assist in downsizing an internal combustion engine. The outcome is that the engine performance and efficiency improve with the use of a hybrid turbocharger. At safe and reliable turbine speeds and optimum compressor efficiencies, the extra flow and pressure at the compressor can be achieved. In comparison to the conventional turbocharger, the hybrid turbocharger will produce more power. The author also suggested further studies on the switching of modes between crankshaft assist and turbocharger assist for optimum performance. Muhammad et al. [8] compared the exergy availability and losses between the Organic Rankine Cycle and Electric Turbo-Compounding (ETC). A Proton 1.6L CamPro CFE turbocharged engine was coupled to a 1 kW electric generator in both systems. The thermal efficiency of both waste heat recovery technologies was determined by calculating the available exergy and exergy losses. 12.5 kW of exergy was available for ORC with exergy losses at 9.7 kW. The exergy losses available for ETC was only 5 kW but the exergy losses were at $8X^{10-3}$. The average thermal efficiency for ORC and ETC was 10.7% and 58.7% respectively. The high exergy losses on the ORC were attributed to the complexity of the system. Liu et al. [9] studied the effects on engine performance of intake e-boosting on gasoline compression ignition engine operating at 2000 rpm engine speed. It was found that e-boosting at the intake manifold substantially improves the IMEP and efficiency of the system. Kristtoffer et al. [10] investigated improving the fuel economy of long-haul heavy-duty vehicles by using an electric turbocharger. It was found that an electric turbocharger improves the fuel consumption in a drive cycle by 0.9%. Hao et al. [11] investigated energy management of gasoline vehicle and the optimisation of hybrid turbocharger. From the study, it was discovered that the electric turbocharger system fuel saving capabilities varies between 1% to 5% over different driving cycles.

Past studies have been done on different types of motor generators to determine their effect on the overall engine performance. Bingyong et al. [12] investigated the use of a brushless DC motor on an electric supercharger controller. The drive motor for the electric turbocharger in this study was a three-phase brushless DC motor. The circuit structure was simplified, and the reliability of the system was improved by selecting a three-phase DC motor without a position sensor. The electric booster double closed-loop control of the engine speed and load control based on effective promotion of pressurisation effect of the engine was achieved under different conditions by obtaining the operating of the engine in actual time. The use of a brushless DC motor improved the reliability of the system. The obtaining of engine speed and load at different speeds under boosting betters the operation of electric supercharger engine.

There were also studies done on the control systems that can be used to govern the energy management of the electric turbocharger system, motor, and battery. Novák et al. [13] used high-speed synchronous motors to electrically drive the compressors in a turbocharger. Torque control of high-speed permanent magnet synchronous motor for the purpose of the driving compressor of supercharged combustion engine was investigated in this study. A lag in the control loop of reference voltage was seen only during the quick start-up of the drive. This lag is of no great significance as quick start-ups of engines are not crucial. Dezong et al. [14] suggested a system for characterisation, control, and energy management for an electrified turbocharged diesel engine in their study. Analysis was done on the effect of the electric machine on the fuel economy and air system variables of the engine. A supervisory level controller and a low-level controller was proposed to generate optimal values of critical variables and track the values, respectively. In both steady-state and transient conditions, the controller was proved to have fast and accurate tracking performance. Supervisory level controller and closed-level controller optimised fuel economy and provided sustainable battery usage, respectively. Desired energy flows were able to be realised by getting the values for air system variables from look-up tables.

Studies were also done on electric turbochargers with emphasis on low engine speeds and different drive cycles to investigate its performance. Pasini et al. [15] evaluated the benefits of incorporating an electric turbo compound into a small twin-cylinder SI engine. A turbocharged engine was developed on an AVL Boost 1D code using experimental maps of two turbines and one compressor. Three different driving cycles and two different vehicle configurations where the first was an electric machine attached to a variable geometry turbocharger (VGT) while the second setup was two electric machines connected at both turbine and compressor respectively was of interest when numerical predictions were done on the model. There was an insignificant reduction in specific fuel consumption when the engine was run at fixed points, whereas fuel consumption improved by 4% when ETC using appropriately sized turbine was run at various speeds and loads. The fuel economy worsens by 2.7% in medium-sized vehicles, while no benefits were observed on small vehicles in terms of fuel consumption in urban cycles. Larger vehicles benefit significantly when ETC is employed. The writers proposed ETC applications like turbine and compressor without mechanical link, both with individual electric drive need to be investigated in greater detail. Hall et al. [16] studied the battery pack requirements for a mild-hybrid system involving an engine with an e-supercharger. It was found that over a drive cycle, a 48 V battery pack improves the fuel consumption between 12 to 15.5%. Zanelli et al. [17] worked on the effect a 12 V or 48 V electric supercharger would have over a drive cycle. It was found that the use of a 12 V electric supercharger improves fuel consumption by 4% over various drive cycles.

Woongkul et al. [18] studied various electric turbocharger compounding, electric turbocharger setups, high-speed machines, power electronics and control techniques with performance on electric forced induction in mind. The researchers summarised the advantages and challenges found from the electric forced induction system available in current times. One of the electric turbocharger setups investigated was the electrically assisted turbocharger (EAT) and electrically split turbocharger (EST). An EAT layout consists of an electric machine, in this case a motor generator is connected onto the turboshaft between the turbine and compressor. The electromagnetic component acts as a generator when power generated at the exhaust manifold is higher than the power demand. This scenario usually plays out at high engine speeds and loads. The electromagnetic components act as a motor when the power demand from the drive cycle is more than the power generated. This is the case when the engine speed and load is low. The advantage of this setup is that it's compact in size and can fit into most engine bays. The motor and inverter that can be used for this layout is also of low rating and is therefore cost-effective. The disadvantage of the EAT is the added cooling needed due to the electric machine becoming ineffective at high temperatures and the need for more power for the turbocharger to operate optimally due to added shaft inertia.

The EST layout is where the turbine is separated from the compressor and both the compressor and turbine are connected to separate electric machines. The electric machine, which is always connected to the compressor, acts as a motor while the electric machine connected to the turbine acts as a generator. Both these electric machines are connected to a battery where it either retrieves energy or stores them. The advantages of this setup are again compact in size like the EAT, but also there is flexibility in controlling energy in and out of the batteries. Besides, as all the exhaust gasses goes through the turbine, there would be no back pressure when a suitably sized turbine is used. One main disadvantage with the EST layout is that it is expensive to implement as the system needs high-rated motors and inverters.

In this study, an electric turbocharging system for both energy recovery and boosting system is modelled in 1D simulation software. The electric turbocharging systems are compared with the conventional turbocharger model in terms of engine performance. The amount of energy available for recovery will be estimated over steady-state full-load operating conditions. The forthcoming section highlights the engine model used for this investigation and its different configurations, followed by the simulation procedure and analysis of the results.

## METHOD

The computational model in this study includes an electric turbocharging system for both energy recovery and air induction system to estimate the amount of energy that can be recovered over steady-state full-load operating conditions. A 2.0 litre SI turbocharged engine model was used as a base for this study. The engine specification for this study is given in Table 1. The engine produces 156.2 kW at 5000 rpm and 298 Nm at 3000- 5000 rpm. The engine is simulated using 1D simulation software in steady-state at engine speed between 1000 -5000 rpm at full-load. The general performance (baseline) of this conventional turbocharger engine is presented in terms of power and torque in Figure 1.

A second engine model was developed where the conventional turbocharger system was replaced with an electric turbocharging system. Two motor generators were added to the engine to implement energy recovery from the turbocharger. The wastegate controller was removed to enable the motor generators to recover the maximum amount of energy besides replacing the role of the wastegate, which was primarily to prevent the turbocharger from over speeding and over boosting. The turbine was separated from the compressor to accommodate the two motor generators that were used. The motor was connected to the compressor to provide electrical assistance to the compressor, whereas the generator was connected to the turbine for energy recovery. The recovered energy was stored in a battery pack. The setup of the electric turbocharger is shown in Figure 2.

**Table 1.** Engine specification for this study.

| Specification | 2.0 litre turbocharged engine |
|---|---|
| Engine type | 4-stroke spark ignition |
| Induction system | turbocharged |
| Fuel delivery | direct injection |
| Compression ratio | 9.5 |
| Bore x Stroke (mm) | 86 x 86.07 |
| Capacity (litre) | 2.0 |
| Maximum Power @5000 rpm (kW) | 156.2 |
| Maximum Torque @ 3000-5000 rpm (Nm) | 298 |

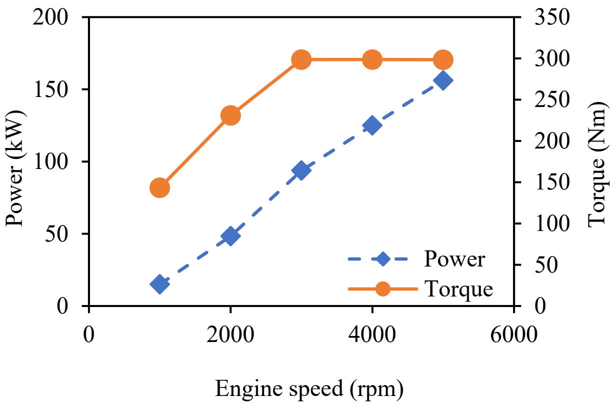


**Figure 1.** Predicted 2.0 litre SI turbocharged engine power and torque performance.

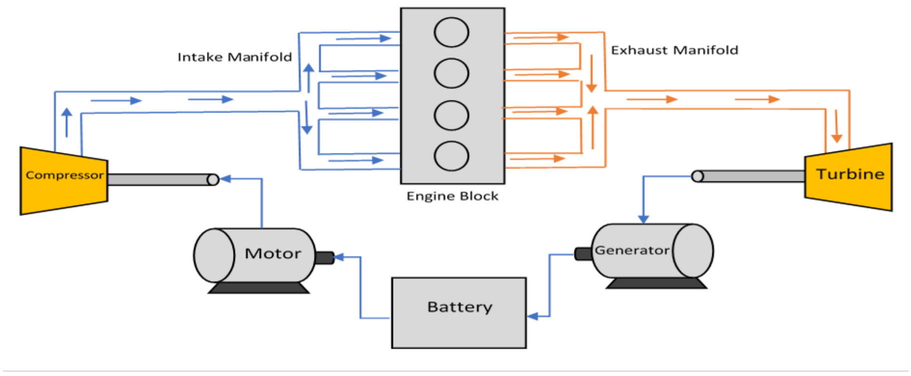


**Figure 2.** The setup of the electrical turbocharger system.

An 11.8-kW motor based on e+a Elektromaschinen und Antriebe AG was used to assist the compressor and recover energy from the turbine. This motor was used as its specification was suitable for the simulation and the torque map was already provided by the manufacturer. The use of two separate motors gives way to flexible power management where the battery plays a crucial role in transferring generated electrical power from the turbine to powering the compressor. Figure 3 shows the torque map that was entered into the motor generator template to simulate the motoring and power generation process.

Since the motor is an angular moving device, angular motion equation was used as a reference for the motor to calculate the amount of power produced by the generator. This equation shown in Eq. (1) calculates the power produced by the motor (P) by multiplying the torque (T) produced by the motor which is obtained from the torque map with the angular velocity (ω) of the motor.

$$P = T\,\omega \tag{1}$$

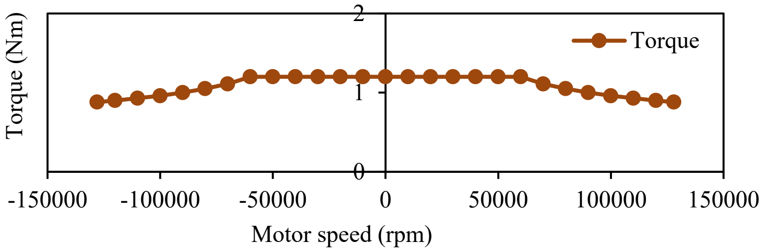


**Figure 3.** Torque map of the motor generator.

Figure 4 shows the amount of maximum amount of electrical power supplied by the motor connected to the compressor in relation to the engine speed. This data was crucial in controlling the amount of electrical energy that the motor supplies from the battery so that it can supply power at different engine speeds. This simple power delivery control setup can also be useful for future transient and driving cycle simulations.

After identifying a suitable motor, the electric turbochargeR engine model was run at full load steady-state to match brake torque and brake power produced by the conventional turbocharger engine model. This was important as both models use the same turbines and compressors. Therefore, there would not be any significant difference in brake torque and brake power produced. Besides, it makes for an easier analysis of other important parameters like BSFC and energy recovered, which is the focus of this investigation. The electric turbocharged engine model was compared with the conventional turbocharger engine model to validate the similarity in its engine performance. Figure 5 shows the comparison between brake torque and brake power produced by the conventional turbocharger and electrical turbocharged engines.

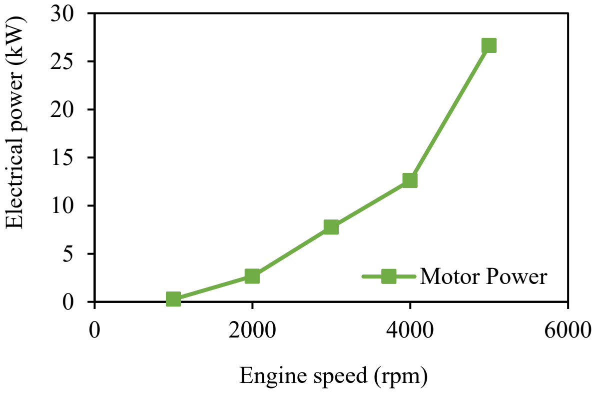


**Figure 4.** Electrical power from motor generator.

The engine performance output between both engines is also similar based on Figure 5. This validates that the electrical turbocharged engine model has the equal engine performance output of the conventional turbocharger engine model matter.

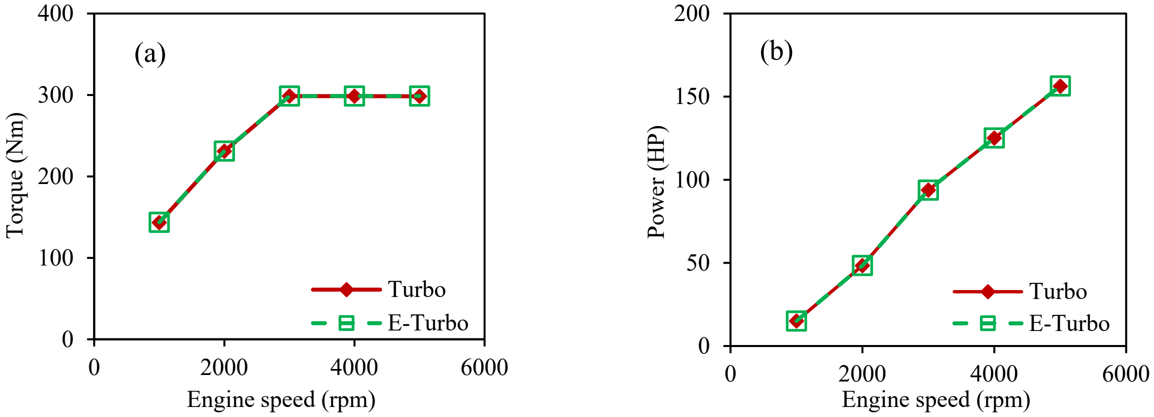
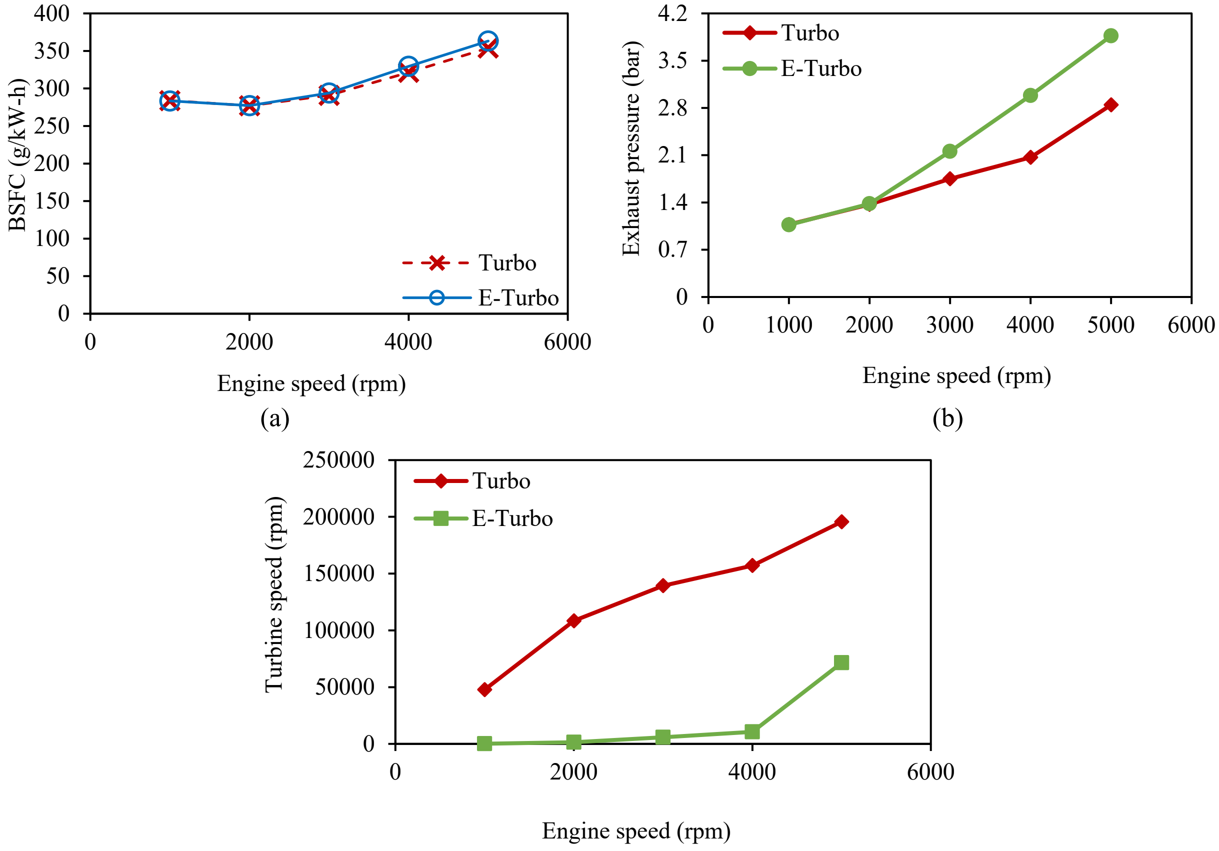


**Figure 5.** Engine performance comparison between the conventional turbocharger and electrical turbocharged engines: (a) brake torque; (b) brake power.

## RESULTS AND DISCUSSION

Figure 6(a) shows the comparison of BSFC between the two engine models. The BSFC is slightly higher in electrical turbocharger throughout the 3000-5000 rpm engine range. The difference in BSFC is more apparent as the engine speed rises with a 2.6% increase in the electrical turbocharged engine over the conventional turbocharger engine. The increase in BSFC is due to the higher back pressure build-up at the exhaust manifold. The increase in BSFC due to engine pumping loss caused by an increase in back pressure was also discussed by Wei et al. [5]. The study involved the use of an additional turbine in series to the charging turbine of the electric turbocharger that was able to recover energy across engine range but suffered from engine pumping loss increase.

Figure 6(b) shows the difference in exhaust pressure between the two engine models. There is an average increase of 20.7% in exhaust pressure across the engine range, with the peak of 35.9% increase seen at 5000 rpm. Figure 6(b) proves that there is an increase in back pressure that causes the increase in BSFC for the electric turbocharger model, especially at the higher rev range. The higher back pressure in the electric turbocharged engine model causes more fuel to be burned for the engine to produce the same brake torque and power as the conventional turbocharger engine model. Although energy is recovered and stored in the battery, the turbine that operates at lower efficiency causes a restriction to air flow which in turn causes the build-up back pressure. The low efficiency operating points was also discussed by Wan Salim et al. in [19] where the conventional turbocharger investigated in the study of fuel-saving technologies only had an average efficiency of 44% which needed further optimisation so that better fuel economy can be obtained.



(a) (b)

(c)

**Figure 6.** (a) BSFC, (b) exhaust pressure and (c) turbine speed data comparison between the conventional turbocharger and electrical turbocharged engines.

Figure 6(c) shows the turbine speed between both engine models. The separation of the turbine from the compressor in the turbocharger causes the rotational speeds of the two machines to be different. The use of a generator to harvest energy causes the turbine speed in the electric turbocharger to reduce by an average of 90% compared to the conventional turbocharger engine. The great reduction in turbine speed causes the turbine to produce less power. Since the turbine efficiency depends on the output power based on the turbine efficiency equation, the turbine becomes inefficient. This equation is shown in Eq. (2) calculates the turbine efficiency (η) by dividing the power output by the turbine (W) with the input power of the turbine (W).

$$\eta = \frac{Output\ Power\ (W)}{Input\ Power\ (W)} \tag{2}$$

The vast change in operating speed of the turbines in the electric turbocharger relative to the conventional turbocharger results in them operating at different points on the turbine efficiency map. Here, the turbine in the e-turbo engine operates at very low efficiency. In this regard, the BSFC of the engine can be improved by resizing the turbine. The motor and generator should also be optimised to increase the level of power recovery in accordance with the turbine used. The optimisation of the electric turbocharger was also discussed by Alias et al. [2], where it was suggested that a suitable design for the electric turbocharging system was needed for the system to achieve optimum efficiency.

Figure 7(a) shows the turbine efficiency between both the conventional turbocharger engine and the electrical turbocharged engine. The average difference in turbine efficiency between both engines is 34.7%. Between 1000-2000 rpm, the turbine efficiency from the conventional turbocharger is 85.02% better than the electric turbocharger. At this speed range, no useful energy is recovered by the turbine from the electric turbocharger as the efficiency is only 10%, whereas the turbine in the conventional turbocharger is playing its designated role in the waste heat recovery process as its efficiency is 61.3%. At engine speeds between 3000-5000 rpm, the change in turbine efficiency between both engines are only 1.2%. The vast difference proves that the turbine operating points in the turbine map vastly changes with the addition of the generator at the turbine, especially at low speeds. The addition of the generator at the turbine causes the turbine to operate at points below the optimum efficiency of the turbine. Thus, this causes inefficient energy recovery as energy from the exhaust gases are still wasted. By optimising the turbine, the energy recovery process can be made more efficient and therefore improve the potential to recovery energy across the whole engine speed range. This was also discussed by Alias et al. [2] when reviewing waste heat recovery technologies concerning electric turbo-compounding. It was suggested by the author that turbine wheels of high efficiency are used to reduce back pressure.

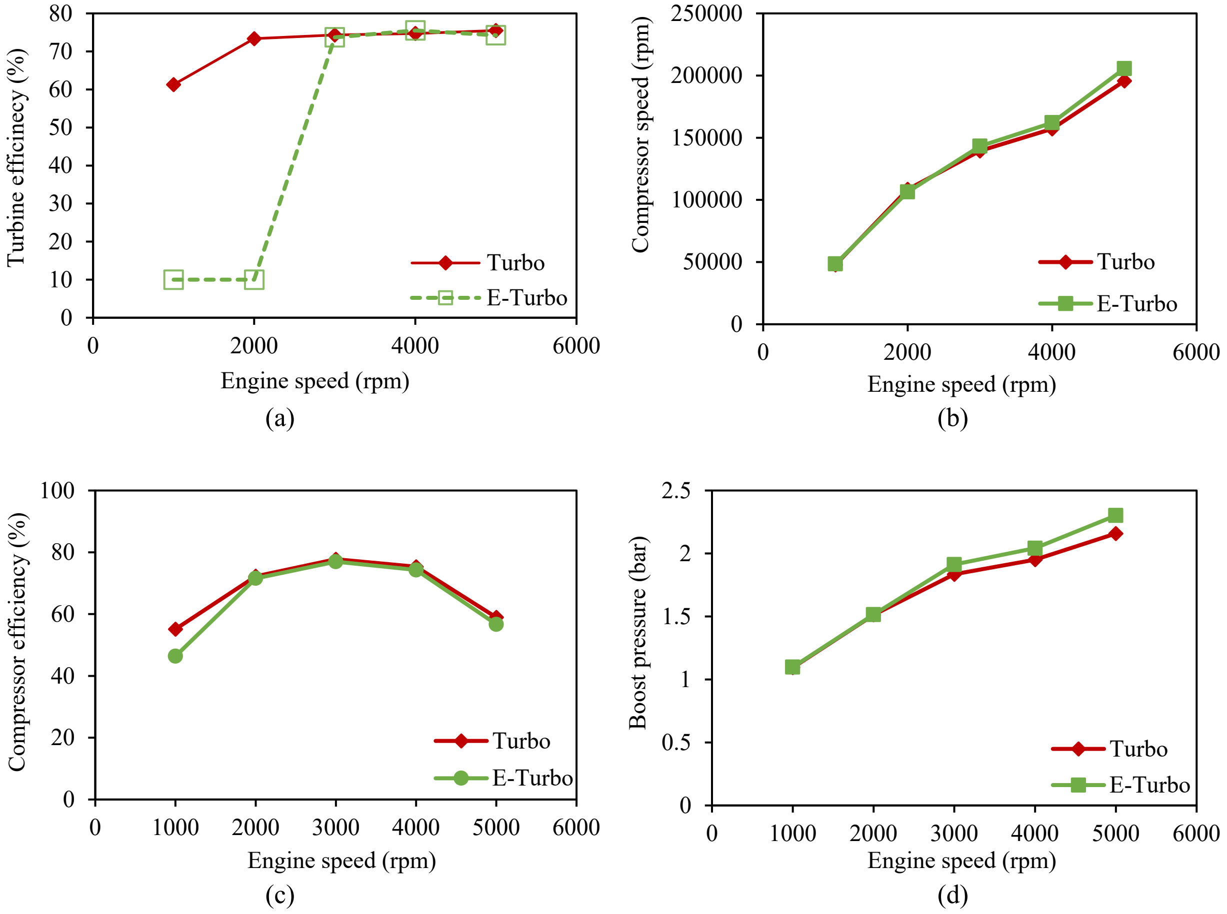


**Figure 7.** (a) Turbine efficiency, (b) compressor speed, (c) compressor efficiency and (d) boost pressure comparison between the conventional turbocharger and electrical turbocharged engines.

As the turbo shaft is separated between the turbine and the compressor for the electric turbocharger, both turbine and compressor have different operating speeds. Figure 7(b) shows the compressor speed comparison between the conventional turbocharger and electric turbocharger engines. The compressor is operating 2.9% faster on the electric turbocharger compared to the conventional turbocharger. This is due to the electrical power supplied by the motor directly to the compressor. At low engine speeds of 1000-2000 rpm, the compressor speeds are nearly similar, with a difference of only 1.7% between both engines. It is only at speeds above 4000 rpm can the change in speeds be observed with the highest between the engines seen at 5000 rpm where electric turbocharged compressor operating 5.1% faster compared to the conventional turbocharger compressor. The slightly higher speeds can be due to more electrical power used from the motor to operate to the compressor rather than depending on the energy transfer of the exhaust gasses and the turbine in conventional turbochargers.

Figure 7(c) shows compressor efficiency comparison between the conventional turbocharger and electrical turbocharged engines. It can be observed that efficiency is similar between both engines at a speed range of between 2000-5000 rpm as the average difference is only 1.8%. The conventional turbocharger has a 15.9% better efficiency compared to the electric turbocharged compressor at 1000 rpm engine speed. Based on Figure 7(c), we can see the optimum engine range for the electrical turbocharger compressor. The low efficiency of the electric turbocharger at low engine speeds can be solved by sending more power through the motor to the compressor so that the compressor operates at optimum efficiency levels at all times throughout the engine speed range.

Figure 9(d) shows the boost pressure comparison between the conventional turbocharged engine and the electrical turbocharged engine. The electrical turbocharged engine produces an average of 3.2% higher boost pressure compared to conventional turbocharged engine across the whole engine range, although the increase is more apparent at high engine speeds. Electrical turbocharger produces 6.6% more boost pressure compared to the conventional turbocharged engine at 5000 rpm engine speed. Although the boost pressure increases with engine speed in the electrical turbocharged engine model, the increase in back pressure caused by inefficient turbines cancels out the gain made from the increase in intake pressure. This scenario was also the discussion by Pavlos et al. in [4] when removing the waste gate by using a larger turbine led to bad engine response and an increase in energy demand by the engine at low engine speeds.

Due to the use of a motor and generator for this study, the amount of power recovered and delivered can be identified and is shown in Figure 8. The amount of energy recovered is 21.6 kW at 5000 rpm, whereas the energy delivered to the compressor is 26.6 kW. However, the maximum value of energy recovered from this engine model should be 11.8kW as that is the maximum amount the motor can produce due to its limitation in terms of operating speed. The difference in the value is due to the angular motion equation used in the motor template as it reads speed above the maximum operating speed of the motor. The system can be optimised by using a motor with a higher maximum operating speed or the use of a wastegate controller as an alternative. The overall trend is that the amount of power delivered to the compressor is higher than the power recovered. This is also due to low turbine efficiency caused by high back pressure. Energy from the turbine can be recovered more effectively by optimising the turbine size, motors and wastegate controllers.

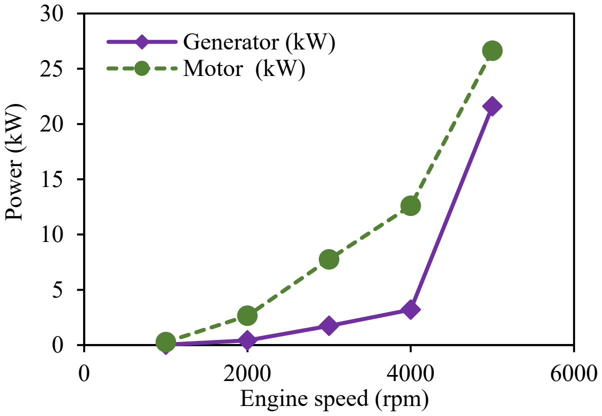


**Figure 8.** Comparison of power recovered and delivered using generator and motor respectively.

## CONCLUSION

The main objective of this study is to evaluate the energy recovery potential of a decoupled electric turbocharger over a steady-state full-load simulation. The modified components of the turbocharger system, such as the motors and battery pack were modelled to have characteristics like an actual component found in a real electric turbocharger. Two engines were modelled to run at full-load steady-state conditions. The conventional turbocharged engine was first run at a steady state to obtain its maximum performance data. Next, the electrically turbocharged engine was derived from the conventional turbocharged engine by making modifications to the turbocharging system, such as decoupling the turboshaft to accommodate the two motors and a battery pack. The electrically turbocharged engine was evaluated in terms of electrical energy recovered, while both engines were compared in terms of BSFC to evaluate the effect on fuel consumption. This study showed that an electric turbocharger engine model could recover energy and deliver it when required besides storing it in a battery pack. The amount of energy that can be recovered from the electric turbocharger is 21.6 kW. The fuel consumption study on both engines found that the BSFC increases by 2.6% in the electric turbocharger compared to the conventional turbocharger due to the build-up of back pressure at higher engine speeds. This is due to the incompatible sizes of the turbines. The findings from this study form the basis for future studies on decoupled electric turbocharged engines in transient drive cycle simulations. The future recommendations can be considered when further this area of research:

i. A suitable and optimised motor generator can open various possibilities in storing and using the recovered energy for other parts of the vehicle, like the air-conditioning system.
ii. A suitably sized turbine and a motor with a higher operating speed can recover and deliver more energy when needed by the engine
iii. A part-load simulation can be done before carrying out a transient drive cycle simulation so that the performance of the turbocharger is accurate, as part-load simulation on the system would help in obtaining data of different operating points of the engine and turbocharger system.

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