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Review

A Review of Range Extenders in Battery Electric Vehicles: Current Progress and Future Perspectives

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Abstract: Emissions from the transportation sector are significant contributors to climate change and health problems because of the common use of gasoline vehicles. Countries in the world are attempting to transition away from gasoline vehicles and to electric vehicles (EVs), in order to reduce emissions. However, there are several practical limitations with EVs, one of which is the "range anxiety" issue, due to the lack of charging infrastructure, the high cost of long-ranged EVs, and the limited range of affordable EVs. One potential solution to the range anxiety problem is the use of range extenders, to extend the driving range of EVs while optimizing the costs and performance of the vehicles. This paper provides a comprehensive review of different types of EV range extending technologies, including internal combustion engines, free-piston linear generators, fuel cells, micro gas turbines, and zinc-air batteries, outlining their definitions, working mechanisms, and some recent developments of each range extending technology. A comparison between the different technologies, highlighting the advantages and disadvantages of each, is also presented to help address future research needs. Since EVs will be a significant part of the automotive industry future, range extenders will be an important concept to be explored to provide a cost-effective, reliable, efficient, and dynamic solution to combat the range anxiety issue that consumers currently have.

Keywords: electric vehicles; range extenders; internal combustion engine; free-piston linear generator; micro gas turbine; fuel cell; zinc-air battery; lithium-ion battery

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1. Introduction

The rapid growth of the global economy and the industrial revolution has increased the demand for energy resources. Currently, a significant portion of energy resources comes from fossil fuels, which are finite and not environmentally friendly [1]. The use of fossil fuels is also a major contributor to climate change, as it leads to an excessive increase in anthropogenic greenhouse gas (GHG) emissions [2]. The global emissions from fossil fuel combustion increased by 90% since the 1970s, reaching over 36.1 Gt in 2014, an all-time high level of emission [3]. In some countries, reducing GHG emissions has become a national priority. For example, Canada aims to reach a 33% reduction in GHG emissions by 2020 and 80% reduction by 2050 from 2007 levels. One of the largest contributors to emissions is the transportation sector. In Canada, road transportation accounts for 82.5% of national transportation emissions, mainly due to the consumption of fossil fuels by internal combustion engine (ICE) vehicles [4]. Pollution generated from ICE can also negatively impact human health.

A promising alternative to ICE vehicles (ICEVs) is electric vehicles (EVs) [5,6]. In the past, there was resistance toward electrification of vehicles since ICE vehicles had been optimized in performance and costs while EVs had not. However, as time passes by, and with more research and development effort being put into EVs, vehicle electrification is currently considered an inevitable part of the future. EVs use a motor, powered by a lithium-ion (Li-ion) battery pack, to propel the vehicle [7]. Li-ion battery is used due to their long lifespan, high energy density, high power density, and environmental benefits [8,9]. EVs have lower environmental and health impacts compared to ICEVs because they do not directly release any emissions or pollutants [10]. NO_x and particulate matters (PMs) are major contributing factors in tail-pipe emissions. From a well-to-wheel standpoint, utilizing a battery EV can reduce PMs by 4 times and NO_x by 20 times [11]. Therefore, EVs can help prevent climate change and protect public health [12]. EVs also play an important role in the development of smart cities in the future [13]. However, due to the lack of available charging infrastructure, the long charge time, the high cost of long-ranged EVs, and the limited range on affordable EVs, there exists a range anxiety issue that hinders the expansion of EVs. Range-extended EVs (REEVs) are seen as a potential solution to the limited range and high cost of EVs.

A range extender is an auxiliary power unit (APU) that provides the vehicle with additional energy to complement the primary battery in propelling the vehicle [14]. According to the 2012 Amendments to the Zero Emission Vehicle Regulations, a range-extended battery EV should comply, among others, with the following criteria [15]:

- The vehicle must have a rated all-electric range of at least 120 km.
- The APU must provide a range less than or equal to the main battery range.
- The APU must not be switched on until the main battery charge has been depleted.
- The vehicle must meet the super ultra-low emission vehicle (SULEV) requirements.
- The APU and its associated fuel must meet the zero evaporative emissions requirements.

An REEV often uses a simple series hybrid powertrain configuration, as shown in Figure 1. There are several different types of range extenders, including ICE, fuel cell, free-piston linear generator (FPLG), and micro gas turbine (MGT). An ICE range extender generates electricity from gasoline using a fuel converter. Some examples of ICE range extending EVs include the Chevrolet Volt and the BMW i3. A fuel cell REEV contains a tank of hydrogen fuel, which gets converted into usable electricity using a fuel cell. An FPLG range extender uses a combustion and linear generator to convert chemical energy into electrical energy. An MGT range extender draws in clean air, compresses it, and passes it through a turbine at extremely high revolutions to generate electricity. In recent years, the concept of a zinc-air (Zn-air) battery as a range extender for EVs has also been investigated. Andwari et al. [16] analyzed the barriers for market penetration of EVs and the technological readiness of different components of battery electric vehicles (BEVs). The authors considered range extenders as the solution to free battery EVs from the 'range anxiety' issue and lower the vehicle weight and capital costs by downsizing the battery. Friedl et al. [17] presented different solutions for range extender in EVs and explained the priorities and practical use for each application. However, the authors only discussed one type of range extender which was ICE. Heron et al. [18] conducted a comparison study on four different range extending technologies while considering several criteria including efficiency, vibration, noise, packaging, cost, emissions, and scalability. However, this study was completed almost a decade ago, and since then, there have been significant developments in the field. The lack of a more recent review of REEVs leads to a significant gap in this research field. The contribution of this paper is a comprehensive and up-to-date review and comparison of five range extending technologies as well as some future research goals for REEVs.

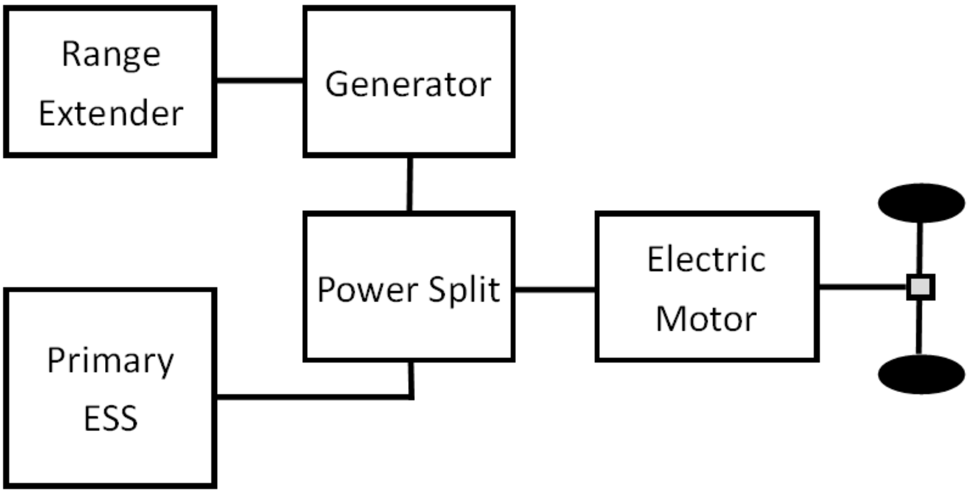


Figure 1. Schematic of a simple series hybrid powertrain with a range extender.

The rest of this paper is organized as follows. Sections 2–6 introduce and discuss ICE, FLPG, fuel cell, MGT, and Zn-air battery as range extenders in electric vehicles, respectively. Section 7 provides a comparison of the reviewed range extending technologies and some future perspectives on these technologies. Finally, some concluding remarks are given in Section 8.

2. Internal Combustion Engine as a Range Extender

2.1. Definitions, Mechanisms, and Pros and Cons

Internal combustion engines (ICEs) are energy generation devices that operate on products of combustible hydrocarbon-based fuels. ICEs use a compressed air/fuel mixture pre-ignition for higher burn efficiency. There are two primary variants based on the ignition type, spark ignition (SI) and compression ignition (CI). SI engines operate on a lower air-to-fuel compression ratio, generally 6–12:1. They use gasoline variants as fuel and make use of the thermodynamic Otto cycle in general applications and the Atkinson cycle when a consistent low-power operation is needed [19]. Modern engines can switch between Otto and Atkinson cycles based on the power demand of the vehicle [20]. CI engines operate using diesel fuel that is 0.8% less in calorific value compared to gasoline. Based on the diesel cycle, the engines operate on a higher air to fuel compression ratio of 14–25:1 [21]. The leaner and higher compression needed for self-ignition leads to a more efficient and cleaner burn. The availability of high torque at lower rotations per minute (RPM) is a significant motivating factor for the use of diesel engines in ICE applications. A recent study indicates that, based on the latest ICE technologies available, fuels with higher hydrocarbons and energy density yield lower CO_2 and CO emissions [22]. The same, however, cannot be stated about NO_x and PMs [23].

ICE-based REEVs are often categorized as a type of hybrid vehicle similar to those available in the market today. They are often mistaken with plug-in hybrid EVs (PHEVs). The ICE-based REEV is a version of a PHEV where the fraction of energy derived from the electric source is higher. What differentiates REEVs from other hybrid EVs is that there is no mechanical link between the engine and the wheels. The ICE, usually compact and lightweight, with its integrated generator, simply charges the battery as necessary, and extends the range of the vehicle. In an PHEV, the ICE can directly supply power to the wheels. Therefore, REEVs requirements are situated somewhere between a PHEV and a BEV, as shown in Figure 2. REEVs should be able to maintain adequate vehicle power with only the battery pack. The ICE would provide power to the battery pack once it has depleted below a certain threshold to avoid irreversible cell damage. The battery should always be charged externally via a standard plug-in, whenever possible. However, with the car being refueled with gasoline in the traditional way, greater flexibility of use is available for longer journeys. In such scenarios, it is imperative that the architecture controller is designed such that it can evaluate all potential routes and assess the topography with the average velocity profile to determine the energy and power requirements during the drive [17]. The Oakridge National Lab performed a study on engine requirements based on degree of electrification and architectural topology [24]. They found that the ICE in an REEV application should be a small engine that can always operate at peak efficiency, since the engine only runs when the battery pack is required to be charged and is otherwise off.

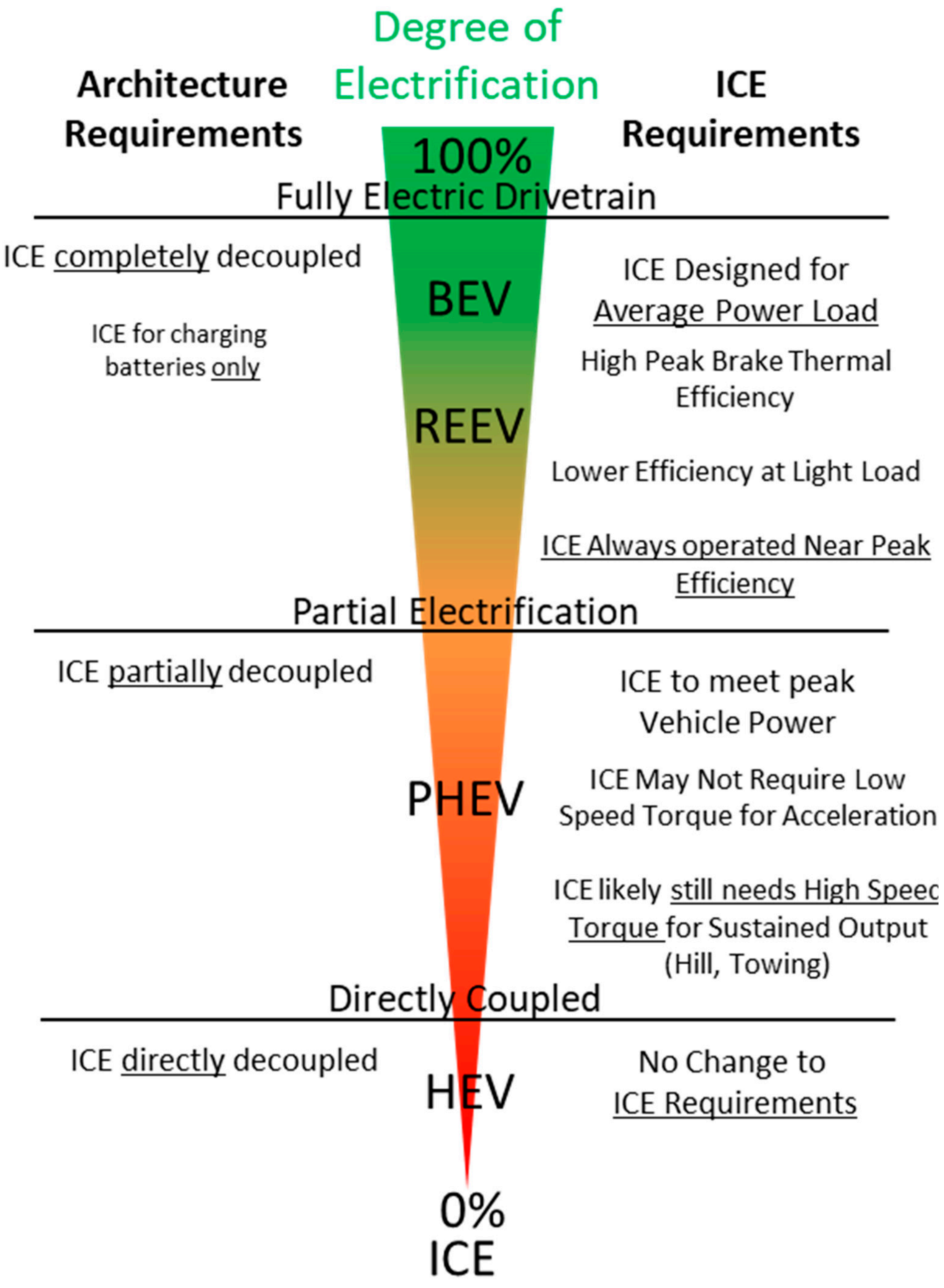


Figure 2. Degree of electrification for different types of electric vehicles.

ICE-based REEVs have several advantages. In over half of North America, cold weather with temperatures averaging below −10 °C is prevalent for one third of the year. In these extreme weather conditions, batteries can lose up to 40% of useful power, due to the increase in internal resistance, and ICE can become a reliable source of energy [25]. Another advantage of having ICE as a range extender is that the utilization factor of the battery pack, or simply the ratio of useful pack energy and total pack energy, can be increased. The battery pack can be developed with a predetermined range of the EV, and all additional power consumption can be derived from the ICE system, which would decrease the cost of the pack significantly. Furthermore, the use of a range extending ICE can have a positive impact on the life cycle of the battery by preventing deep cycle degradation of the pack [26]. Finally, the integration of ICE into EVs is simple and straightforward, as the system is well-understood, and the fuel infrastructure already exists on a very large scale. However, there are also a few disadvantages that need to be considered for ICE-based REEVs. The quietness of battery EVs serves as an attractive marketing point about the vehicle type. However, with ICE as a component in the powertrain, there will be additional noise and vibration. Some other disadvantages are the low efficiency and the high emission level that comes with ICE. One of the most important aspects to consider in the argument to transition to EVs from ICEVs is the benefits to the environment. If ICE is still utilized, even at a lower level, it will still affect the environment negatively with its emissions.

2.2. Recent Research Developments

The use of ICE in REEVs has been a point of focus for many research and development groups, in both academic and industrial settings. Borghi et al. [27] reviewed the design and experimental development of an original range-extender single-cylinder two-stroke ICE, rated at 30 kW with the maximum engine speed of 4500 rpm, and addressed the typical issues affecting conventional engines of this type. The new engine was also compared to a standard four-stroke engine. The authors observed several main advantages of the two-stroke ICE, such as lower weight, higher brake efficiency, less heat rejected, and lower thermal and mechanical loads within the cylinder. However, it was found that the new engine could not meet the compliance requirements of the very low NO_x limit of standard EVs, which were stated by the authors to be addressed in a future phase of the study. Solouk et al. [28] investigated the optimal fuel consumption improvement of an experimentally developed 2-L multi-mode low-temperature combustion (LTC)-SI range extender in a light-duty BEV. The LTC engine, including homogeneous charge compression ignition (HCCI) and reactivity-controlled compression ignition (RCCI), can improve fuel consumption and reduce NO_x. The results showed that the HCCI and RCCI range extenders achieved 11.0% and 5.4% fuel consumption improvement over a single-mode SI range extender, respectively, in the city driving cycles. These improvements increased to 12.1% and 9.1% in the highway driving cycles.

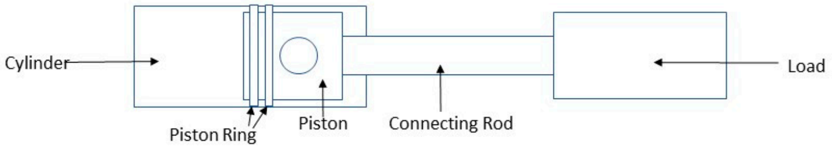
Aside from studies in academia, there have also been several actual products developed by industrial organizations. The FEV group introduced its ECOBRID mild hybridized diesel engine, which is a 1.6-L, four-cylinder engine equipped with an e-turbo, a 6.5 kW energy storage system, a 48 V, 12 kW P0 motor, an exhaust gas recirculation (EGR) system, a diesel particle filtration (DPF) system, and a battery management system that allows both waste heat and kinetic recovery as well as reduced integration complexity due to the standalone nature of the package [29]. Another product is the FEV mild hybridized diesel engine [30]. FEV stated that by 2025, the cost of a 300-km battery EV would be the same as their mild hybridized counterpart, and beyond that range, their hybridized system would be more cost efficient. Since REEVs operate better with the ICE running at constant speeds, the advancement in e-compressor, turbocharger, and engine downsizing are aspects that still apply to the development of ICE in an REEV application.

Another reputable engine is the MAHLE Modular Hybrid Powertrain (MMHP), which consists of a compact turbocharged 900-cc ICE that can be modularly equipped with one, two, or four-speed transmission [31]. This ICE has a maximum power of 30 kW and the generator was specified to match this output [32]. A battery pack rated at 14 kWh is required and a traction motor with 100 kW peak output is selected, to provide a minimum electric-only range of 70 km. The MMHP has a combined battery and engine range of up to 500 km, before recharging or refueling is required. The engine only weighs 70 kg with the generator and can be installed vertically or horizontally. It has also been calibrated for compliance with Euro 6 regulations and is capable of achieving 45 g CO_2/km on the legislated New European Driving Cycle (NEDC) test.

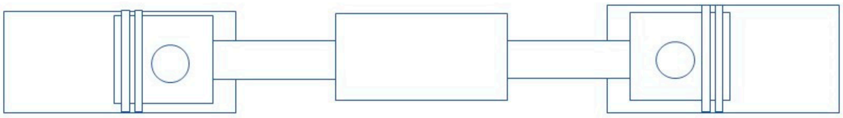
3. Free-Piston Linear Generator as a Range Extender

3.1. Definitions, Mechanisms, and Pros and Cons

Free-piston linear generator (FPLG) is a technology that has been around for a while. It is an internal combustion engine that does not have a crankshaft. FPLG is considered by some to be the solution to the range anxiety issue in EVs and has seen some advancements recently. The first research into FPLGs occurred in the 1920s, for their use as gas compressors and gas generators. General Motors and Ford considered introducing free-piston engines in the 1960s. However, during that time, traditional ICEVs were the more reliable and fuel-efficient solution [33]. The German Aerospace Center (DLR) is one of the first organizations to research and develop a FPLG as a range extender for EVs [34]. FPLGs are often categorized based on their piston assembly [35]. The different classifications can be seen in Figure 3. An FPLG often consists of a free-piston engine and a linear alternator/load converter. It functions by the combustion increasing pressure in the chamber and driving the motion of the piston. The linear load converter is then able to convert the piston's motion into electrical energy [36]. When utilized as a range-extender, the FPLG provides the EV with the additional electrical energy to charge the batteries [34].



Single-piston linear engine configuration



Dual-piston linear engine configuration

Opposed-piston linear engine configuration

Four-cylinder complex configuration

Figure 3. Different configurations of free-piston linear generator.

The advantages of using FPLGs as range extenders can be attributed to the absence of the crankshaft. For instance, not having the crankshaft results in easily adjustable compression ratios, which allows FPLGs to be compatible with a variety of different fuels, such as diesel, gasoline, natural gas, and hydrogen [35]. Some other advantages of FPLGs in comparison with ICEs are their simplistic design, high efficiency, long service life, low friction, and low maintenance costs [37]. They are also compact, allowing for an easy integration into vehicles by placing them in the floorboards [34]. Moreover, FPLGs have a quicker power stroke while also operating at lower temperatures, which should theoretically reduce emissions [38]. However, FPLGs are still early in the experimental phase and have not been tested on a commercial scale. Some issues with them include detent force, inconsistent start, combustion, misfiring, and lubrication [39].

3.2. Recent Research Developments

Jia et al. [36] investigated free-piston engines by comparing two- and four-stroke thermodynamic cycles. It was found that when operated in a four-stroke cycle, the piston's motion was more irregular since the linear generator was used as a motor and a generator. Further, in the four-stroke cycle, under half the recorded power was lost due to pumping the motoring process. Four-stroke cycles were found to have a higher thermal efficiency despite a narrower power range. The two-stroke cycle appeared to have its heat releasing process similar to a constant volume process, as well as a lower peak cylinder pressure and compression ratio. Kock et al. [34] detailed the progress the DLR had made in creating a FPLG to be incorporated into an REEV. The authors outlined the process the DLR followed and indicated that best results were found when the subsystems are built separately, hence, less reliant on each other, and then assembled. Rathore et al. [39] explored FPLG as a whole and by its subsystems. The authors reviewed different types of FPLGs based on piston arrangements. Possible piston arrangements are single piston, dual combustion chamber, and opposed piston. Single piston has the advantage of the simplest design while maintaining good controllability. Dual combustion chambers do not require a gas spring which allows them to be more compact, leading to a higher power to weight ratio. The challenge with the dual combustion chamber is controlling the piston's motion, particularly the stroke length and the compression ratio. The opposed piston allows the engine to be completely balanced and free from vibration, which saves space and leads to a less complex design. FPLGs can also be categorized by generator shapes, which are tubular and flat. The tubular-type FPLGs provide better efficiency. However, the challenge is in the manufacturing and assembly of the magnetic ring, lamination stacked stator, and windings. The flat-type FPLGs have some contradicting results, with some experiments showing that they have the better fuel efficiency. Despite the structural drawbacks, flat-type generators have greater specific power, output current, and voltage, making them more suitable for FPLGs. Guo et al. [33] summarized the recent developments of free-piston internal combustion engine linear generators that function with gasoline and diesel. It was stated that the gasoline FPLG had an unstable combustion process and suffered from frequent misfiring. The diesel FPLG faced a challenge being the cold start-up process. Toyota Central R&D Labs Inc. discovered a power output of 10 kW and a maximum energy conversion efficiency of 42% for their prototype, which was a single-cylinder FPLG with SI and PCCI combustion. Hung et al. [35], upon examining piston dynamics, found that the implementation of springs in FPLGs can increase the piston velocity and overall engine performance. When analyzing the compression ratio and the optimization of the combustion process, it was concluded that the transition from SI combustion to HCCI combustion produced the best results. HCCI combustion has several advantages including lower in-cylinder peak temperatures and lower NO_x emissions. Mikalsen et al. [38] designed a modular compression ignition FPLG. They outlined their simulations and highlighted the key advantages of their prototype over conventional engines. Xu et al. [37] designed an accurate simulation model of a two-stroke free-piston engine and validated their results with experimental data. The model was then used to study various FPLG characteristics such as the influence of piston assembly mass, the timing of air intake and exhaust on piston motion characteristics. The results showed the change rules of piston displacement, the velocity, and frequency changes with air pressure, the piston assembly mass, and the optimal air intake position of the linear generator.

4. Fuel Cell as a Range Extender

4.1. Definitions, Mechanisms, and Pros and Cons

Fuel cells are devices that transform chemical energy into electrical energy [40]. They are categorized into five groups based on the operating temperature and materials used, which are alkaline fuel cell, solid oxide fuel cell, phosphoric acid fuel cell, polymer electrolyte fuel cell, and molten carbonate fuel cell [41]. The first fuel cell prototype was developed in 1839 by William Grove, but it was not until the 1990s when fuel cells started to gain interest in the market for small stationary applications [42]. A fuel cell contains an electrolyte and two electrodes which are called anode and cathode [43]. Hydrogen is fed to the anode and splits into a proton and an electron. The proton passes through the electrolyte while the electron goes through an external circuit and a load, resulting in chemical energy being converted into electrical energy. The proton and electron combine with oxygen to produce some heat and water. Because of its ability to store energy physically, in the form of hydrogen, fuel cells have been considered by some to be a promising component in commercial vehicles such as cars and buses [44]. Fuel cells have a practical efficiency of 32–38%, with a theoretical efficiency of 80% [45]. Aside from having high efficiency, they also have high energy and power density. Fuel cells can power vehicles by themselves or as a range extender, as shown in Figure 4, and have shown promising performance results in these applications [45,46]. However, fuel cells are significantly more expensive than ICEs and batteries. In order to lower the cost of fuel cells and make them a viable option to be used in EVs, material and manufacturing costs must be addressed [45]. Moreover, for fuel cells vehicles to gain more traction, a significant investment in hydrogen generators and refueling stations must be made. Fuel cells are currently seen to be more viable to be used in an REEV than a full fuel cell EV, because of the cost and safety of the system [46]. In order to store the hydrogen required to power a fuel cell, liquid hydrogen tanks are preferred. They have an energy storage density of around 1.3 kWh/L compared to gaseous hydrogen tanks which have an energy storage density around 0.36 kWh/L [47].

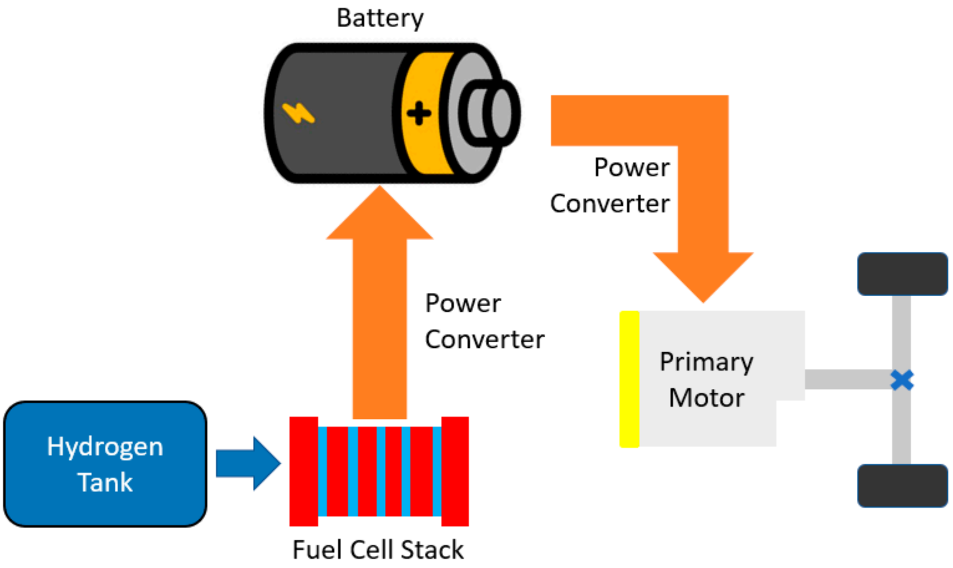


Figure 4. Architecture of a powertrain with fuel cell as range extender.

Some advantages of fuel cells include fast refueling, fast start-up capability, low noise and vibration, great driving range, compact size, and low weight [48]. Other advantages of fuel cell are high energy efficiency and low emissions resulting in minimal pollution [49]. However, the hydrogen fuel used in fuel cells does not naturally occur and still requires energy to be produced. This energy often comes from fossil fuels, thus still producing emissions overall [45]. There are several disadvantages of fuel cells that need to be considered and improved. The high purity hydrogen required for the fuel cell to work at maximum capability and the possibility of trace contaminants in the fuel itself can result in potential poisoning [41]. Scaling fuel cells requires creating a fuel stack from multiple fuel cells to maximize their lifespan, reliability, and power output. However, stacking multiple fuel cells can result in a lack of structural integrity, non-uniform potential, and product flow distributions [50]. In addition, as discussed previously, the cost of fuel cells needs to be reduced to make them more viable to be used in larger applications such as EVs.

4.2. Recent Research Developments

There have been several studies recently with the goal of improving and further developing fuel cells as EV range extenders. Udomslip et al. [48] developed a metal supported solid oxide fuel cell (SOFC), enabling a performance increase up to a factor of 10 and demonstrating the effectiveness of target-oriented optimization of processing and microstructure. The fuel cell consisted of an optimized anode structure, a 2-mm thin-film electrolyte, and a highly active $La_{0.58}Sr_{0.4}CoO_{3-\delta}$ (LSC) cathode. The enhanced cells provided a current density of 2.8 A/cm^2 at 650 °C and 0.7 V, setting a benchmark for other SOFC performance. Geng et al. [51] studied and compared an on-off control strategy, a power following control strategy, and a fuzzy logic control strategy for fuel cell REEVs to improve the power and economic performance. The simulation results indicated that using the power following fuzzy logic algorithm can improve the performance of fuel cell REEVs, particularly acceleration (accelerating time from 0 to 50 km/h of 8.9 s) and mileage (total mileage of 286.7 km). Liu et al. [52] proposed a novel multi-objective hierarchical prediction energy management strategy to achieve optimal fuel cell life and energy consumption in REEVs. The algorithm combined the direct configuration method and sequential quadratic programming based on the predicted speed and state of charge reference. Simulation results showed that the proposed strategy is more cost-effective than the charge depletion-charge sustaining strategy and the equivalent consumption minimization strategy. Fernández et al. [53] developed a powertrain design for EVs with a hydrogen fuel cell stack system operating as a range extender. The goal was to study how optimization techniques using genetic algorithms could be a significant factor when planning the fuel consumption and selection. Dimitrova et al. [54] investigated a novel SOFC system with gas turbines to be used as a range extender, which has an energy efficiency of around 70% in simulation. The novel system also included an integrated on-board fuel reforming using a liquid fuel, which consisted of methane produced from biomass and liquefied at a pressure of 200 bars in the vehicle tank. This eliminated the need for storage of hydrogen gas. The optimal design of the module was found to extend the range of EVs by over 600 km, with an emission of 30 g CO_2/km. Fernández et al. [55] modified the structure of the power plant of a fuel cell REEV and stated that it can be used commercially until the deployment of a full electric or hydrogen recharge network is fulfilled. The authors also conducted a study to determine the working conditions that would result in better efficiency and performance of both energy sources in the REEV, electricity stored in a Li-ion battery, and hydrogen gas in high pressure tanks.

5. Micro Gas Turbine as a Range Extender

5.1. Definitions, Mechanisms, and Pros and Cons

Micro gas turbines (MGTs) are small and high-speed gas combustion turbines that have a power output ranging from 30 kW to over 200 kW [56]. MGTs can operate as range extenders in EVs because they act as generators that can charge the depleted Li-ion battery [57]. They appeared in the automotive market in the 195 and were designed to be used in aircraft, commercial buses, and missile launching stations [58]. MGTs typically consist of a turbine, a generator, a combustor, an alternator, and an air compressor, as shown in Figure 5 [59]. The turbine propels the compressor, which compresses the air and the generator simultaneously. Air is then drawn from the compressor into the recuperator, which acts as a heat exchanger, recovering the heat from the exhaust gas. Afterwards, the heated air travels to the combustor chamber where fuel is also added. In the combustor chamber, the combusted mixture expands, causing the turbine and the shaft to rotate and generate electricity.

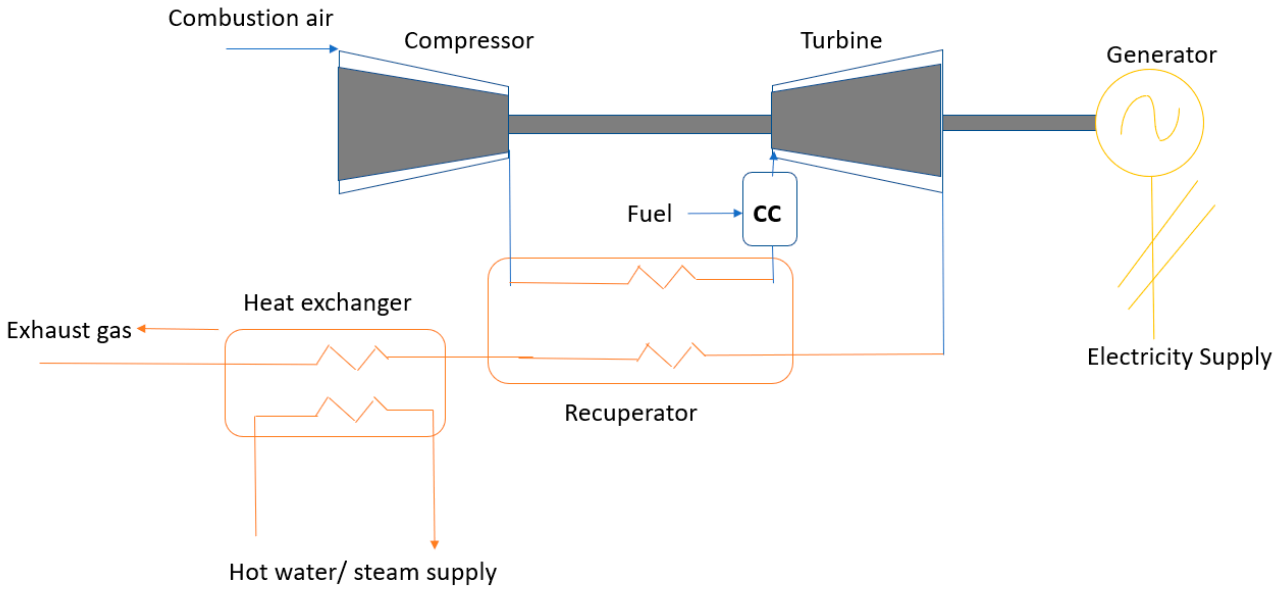


Figure 5. Schematic of a micro gas turbine generator.

Some advantages of using MGTs as range extenders include the compact size which takes up less space, low maintenance costs, ease of operation, and low NO_x emissions [58]. MGTs also have long overall lifetime of 2000 to 8000 h at an operating temperature of 10 °C [57]. When compared to conventional SI engines, the CO_2 emissions of MGTs are 1.3% to 19.6% lower [58]. However, since MGTs are scaled down versions of regular gas turbines, the turbine efficiency and power are reduced, resulting in a very high shaft speed, and requiring power inverters to generate electricity [59]. Another disadvantage of MGTs is their overall higher costs.

5.2. Recent Research Developments

There have recently been some research studies looking into the feasibility of MGT as a range extender in EVs. Ribau et al. [60] compared the energy efficiency and CO_2 emissions of different range extender engine solutions, including a four-stroke engine, Wankel engine, and MGT. The results showed that the MGT achieved 2.8–10.7% less energy consumption than the baseline battery EV, but it also produced 1.3–19.6% more CO_2, which was believed to be caused by the low efficiency of the MGT. Shah et al. [61] developed a method to investigate the effect of the air filtration systems in MGTs in terms of gaseous emissions and electrical power output. Using a 28 kW MGT and a vehicle simulation using NEDC, six experiments were performed, with three using an air filter and three not using an air filter. The experimental results showed that an air filtration system would be feasible in MGT applications without any loss of performance. The electrical power output efficiency was also found to improve using the air filtration system. Ji et al. [57] formulated a systematic design methodology for the MGT range extender and explored its feasibility in EVs. The authors constructed an MGT simulation model, which included exhaust pipes, a compressor, inlet pipes, a turbine, a recuperator, and a combustor, to investigate the MGT thermal efficiency, the transient performance, the effect of MGT addition on an REEV, and the performance of the REEV. The results showed that the MGT range extender has an advantage over the ICE range extender in terms of emissions, as the ICE generated 32 g NO_x and 79.8 kg CO_2 per kg of fuel while the MGT only released 2.53 g NO_x and 7.12 kg CO_2 per kg of fuel. It was also found that the thermal efficiency of MGT could reach 35% when the recuperator effectiveness was 0.7, the pressure ratio was 3.2, and the turbine inlet temperature was 1152 K. Kontakiotis et al. [62] used a parametric study to examine the performance of an EV powertrain consisting of an MGT, a battery pack, and a traction electric motor, in order to determine the requirements for an REEV that could become competitive, in terms of fuel consumption and pollutant emissions. A capstone model C30 micro turbine operated by natural gas at full load power was used in the experiment and the simulation. Experimental results showed a strong influence of the ambient temperature on the MGT performance and a 20–30% discrepancy between simulated and experimental results. Tan et al. [63] developed a computational vehicle model to analyze the impact of driving conditions on the driving range of an REEV and the sizing of the MGT range extender. Simulation results showed that, with a 10-kW range extender, the REEV had a similar driving range to an ICE vehicle. The shaft power for the MGT peaked at 9.5 kW at a temperature of 1200 K and was limited by the turbine operating pressure.

6. Zinc-Air Battery as a Range Extender

6.1. Definitions, Mechanisms, and Pros and Cons

Zn-air is a type of metal air battery that consists of an air cathode and a zinc anode. Zn-air batteries can work as a range extender because they possess a high specific energy and a good resistance to degradation from aging, allowing them to be an efficient energy storage source for an REEV [64]. A full battery EV requires a large Li-ion battery pack which can be expensive. In an REEV, with a Zn-air battery pack serving as a range extender for longer trips, the Li-ion battery pack can be significantly smaller and only used for daily commutes [64]. The concept of Zn-air batteries was first discovered in 1840, with the first commercial Zn-air battery arriving in the market in 1932 [65]. However, Zn-air batteries are not currently used commercially in EVs [66]. In the Zn-air battery cell, oxygen enters the gas diffusing electrode and is reduced by electrons coming from the anode where zinc is oxidized [67]. Oxygen then reacts with the water and the catalyst, becoming OH^- ions. The OH^- ions travel to the anode and react with zinc to form zincate $Zn(OH)_4{}^{2-}$ and two electrons which are the electrical energy released by the battery. Finally, the zincate decomposes to recycle all of the chemicals, except for oxygen which is supplied by the environment.

Zn-air batteries have several promising upsides. They have a greater specific energy and energy density than Li-ion batteries, theoretically making them a great solution to the range anxiety issue [64]. They are also easier to manufacture and made from more common, less expensive materials, making them more cost-effective. Zn-air batteries prove to be a safer option compared to other batteries used in EVs [68]. Furthermore, they have a high energy efficiency and a long lifespan [67]. In comparison to gasoline engines, the Zn-air range extender has lower tailpipe emissions [69]. However, there are some problems that need to be addressed before Zn-air can be used commercially in EVs. CO_2 can alter the pH of the cell's electrolyte, harming the electrolyte conductivity. The cell can also be dried out if the incoming air does not have the appropriate humidity level [66]. Zn-air batteries suffer heavily from cycle degradation, limiting their cycle life [64]. Some other issues with Zn-air range extender include the dendrite formation at the zinc anode, further advancements of air cathode materials for commercialization, and the slow process of converting energy in the cell [65,67].

6.2. Recent Research Developments

Even though Zn-air batteries are not widely researched for use in EVs, there have been some studies that investigated the feasibility of Zn-air as a range extender. Eckl et al. [70] stated that a range of 100 km per day is suitable for 90% of the daily trips in a year in Germany. The authors used a Zn-air range extender with a peak power of 4 kW and an energy content of 4 kWh to produce some promising results. Cano et al. [68] stated that Zn-air batteries could be the future of EVs. The authors claimed that the potential is greater when combining a Zn-air battery with a Li-ion battery in a dual battery configuration. Catton et al. [69] modeled and compared various powertrains including an REEV with Zn-air, a conventional gasoline powered vehicle, a fuel cell vehicle, and an REEV with ICE. The comparison criteria included energy consumption, range, life cycle and tailpipe emissions, cost, and consumer acceptance. The results for the Zn-air REEV showed lower tailpipe and greenhouse gas emissions compared to the ICE REEV, while being able to maintain a similar driving range. Sherman et al. [66] designed a powertrain consisting of a Li-ion battery supported by a Zn-air battery as a range extender. In simulation, the vehicle performance compared favorably to a full battery EV with a single Li-ion battery, travelling up to 75 km further in total while having a significantly lower cost. The simulation also demonstrated that the Zn-air battery could reach a ten-year lifespan under certain conditions. Tran et al. [64] expanded on the same powertrain concept, and further analyzed the environmental and economic benefits of the Zn-air REEV. Their powertrain architecture proposal is shown in Figure 6. It was found that the cost of Zn-air REEVs were 15% lower than that of full battery EVs. Furthermore, the costs associated with air pollution would decrease by 44.8% with the mass rollout of REEVs.

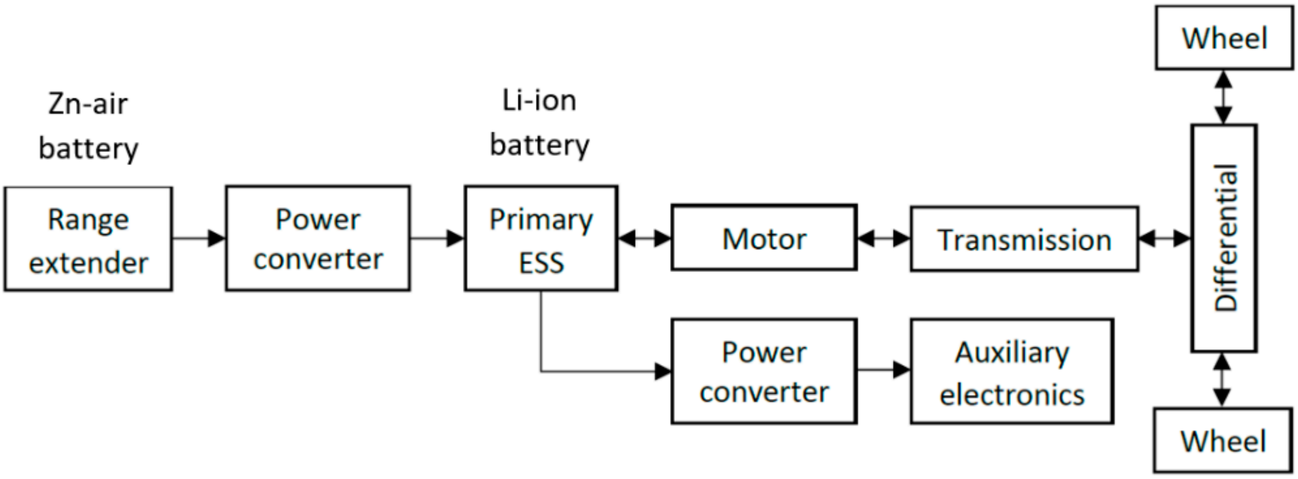


Figure 6. Powertrain architecture with zinc-air battery as a range extender. Adapted from [64].

7. Comparison of Range Extending Technologies and Their Future Perspectives

Overall, the criteria for an ideal range extender include low cost, high efficiency, high power, and energy density, established fuel infrastructure, simple design, easy and flexible packaging, good scalability, low noise and vibration, low emissions, and long service life. There has been some progress made to improve each of the discussed EV range extending technologies to satisfy the ideal requirements, but they still have certain practical limitations. The working mechanisms, advantages, and disadvantages of the range extenders are summarized and compared in Table 1. Researchers should take these points into consideration when working to improve the respective type of range extender.

Each range extending technology has its own advantage but still requires more research and development to address the downsides. The ICE range extender needs to improve its efficiency and reduce the emissions. The FPLG needs to address the issues with noise and vibration. Fuel cell range extenders' priority is their high costs and lack of fuel infrastructure. MGTs needs to increase their efficiency and start-up time. Zn-air battery range extenders require more work before commercialization. Aside from the individual disadvantages of each EV range extender type, there are some challenges they all face, and these challenges should be addressed in future research activities to improve the performance and reliability of range extenders and ultimately REEVs. Specifically, they need to be appropriately integrated into the EVs, which means there are criteria to focus on, in terms of propulsion controls, mechanical design, and electrical design [71,72]. Energy management is also an important aspect in REEVs since an effective supervisory controller is required to determine when to use the primary Li-ion battery and when to use the range extender, so that the costs and performance of the EVs are optimized [73]. It is undeniable that EVs will be a significant part of the automotive industry future, and REEVs will be an important concept to be explored, because of the potential for a cost-effective, reliable, efficient, and dynamic vehicle, with a long driving range to combat the range anxiety issue that consumers currently have.

Table 1. Comparison of different range extending technologies in electric vehicles.

Range Extender	Distance Added	Advantages	Disadvantages	Related Research
Internal combustion engine	150–420 km	Low cost; High power density; Easily implemented due to established fuel infrastructure; Good scalability; Fast start-up.	Low efficiency; High emissions; No packaging variability; Issues with noise and vibration.	[24–29]
Free piston linear generator	~600 km	Compatible with a variety of fuels; Simple design; Low-to-mid cost; Long service life; Compact size; Good scalability.	Detent force; Inconsistent start; Some emissions; Low power density; Issues with noise and vibration.	[30–36]
Fuel cell	60–240 km	High efficiency; Good packing variability; High power density; Low emissions; No issue with noise and vibration; Compact size.	High cost; No fuel infrastructure; No flexibility of fuel; Susceptible to contaminant poisoning.	[45,48–52]
Micro gas turbine	~45 km	Compatible with a variety of fuels; Long service life; Low emissions; No issue with noise and vibration; Compact size.	High cost; Low efficiency; Low power density; Slow start-up.	[54,57–60]
Zn-air battery	~75 km	High energy density; Low cost; Easy to manufacture; Safe to use; Long lifespan; Low emissions; No issue with noise and vibration.	Not yet optimized for commercialization; Highly susceptible to cycle degradation.	[61,63,65–67]

8. Conclusions

Transportation is currently contributing significantly to climate change and pollution-related health problems, as most vehicles on the road are conventional gasoline vehicles with high emission levels. EVs are considered a promising alternative to ICEVs because they do not directly release any emissions or pollutants. However, the expansion of EVs on the market is hindered due to a variety of limitations such as to the lack of available charging infrastructures, the long charge time, the high cost of long-ranged EVs, and the limited range on affordable EVs. These issues for consumers are commonly grouped and called range anxiety. One solution to the range anxiety issue is the use of range extenders, which are devices that provide the vehicle with additional energy to complement the primary battery. This paper introduced and discussed five prominent range extenders used in REEVs, including internal combustion engine, free-piston linear generator, fuel cell, micro gas turbine, and zinc-air battery. The comprehensive review included basic definitions, working mechanisms, advantages, and disadvantages of each technology, as well as a summarized comparison between them. Recent research developments and findings for each range extender were also discussed. This review paper on EV range extending technologies serves as a basis for researchers to study and develop more efficient, reliable, and practical range extenders in the future to improve vehicle performance and assist in the transition from ICEVs to EVs.

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References

1. Apostolou, D.; Xydis, G. A literature review on hydrogen refuelling stations and infrastructure. Current status and future prospects. *Renew. Sustain. Energy Rev.* **2019**, *113*, 109292. [CrossRef]
2. Aldhafeeri, T.; Tran, M.-K.; Vrolyk, R.; Pope, M.; Fowler, M. A review of methane gas detection sensors: Recent developments and future perspectives. *Inventions* **2020**, *5*, 28. [CrossRef]
3. Shamsi, H.; Tran, M.-K.; Akbarpour, S.; Maroufmashat, A.; Fowler, M. Macro-level optimization of hydrogen infrastructure and supply chain for zero-emission vehicles on a Canadian corridor. *J. Clean. Prod.* **2021**, *289*, 125163. [CrossRef]
4. Perera, P.; Hewage, K.; Sadiq, R. Are we ready for alternative fuel transportation systems in Canada: A regional vignette. *J. Clean. Prod.* **2017**, *166*, 717–731. [CrossRef]
5. Panchal, S.; Gudlanarva, K.; Tran, M.-K.; Fraser, R.; Fowler, M. High Reynold's number turbulent model for micro-channel cold plate using reverse engineering approach for water-cooled battery in electric vehicles. *Energies* **2020**, *13*, 1638. [CrossRef]
6. Tran, M.-K.; Mevawala, A.; Panchal, S.; Raahemifar, K.; Fowler, M.; Fraser, R. Effect of integrating the hysteresis component to the equivalent circuit model of Lithium-ion battery for dynamic and non-dynamic applications. *J. Energy Storage* **2020**, *32*, 101785. [CrossRef]
7. Tran, M.-K.; Fowler, M. Sensor fault detection and isolation for degrading lithium-ion batteries in electric vehicles using parameter estimation with recursive least squares. *Batteries* **2019**, *6*, 1. [CrossRef]
8. Mevawalla, A.; Panchal, S.; Tran, M.-K.; Fowler, M.; Fraser, R. Mathematical heat transfer modeling and experimental validation of lithium-ion battery considering: Tab and surface temperature, separator, electrolyte resistance, anode-cathode irreversible and reversible heat. *Batteries* **2020**, *6*, 61. [CrossRef]
9. Mevawalla, A.; Panchal, S.; Tran, M.-K.; Fowler, M.; Fraser, R. One dimensional fast computational partial differential model for heat transfer in lithium-ion batteries. *J. Energy Storage* **2021**, *37*, 102471. [CrossRef]
10. Tran, M.-K.; Fowler, M. A review of Lithium-Ion battery fault diagnostic algorithms: Current progress and future challenges. *Algorithms* **2020**, *13*, 62. [CrossRef]
11. Van Mierlo, J. The World Electric Vehicle Journal, The Open Access Journal for the e-Mobility Scene. *World Electr. Veh. J.* **2018**, *9*, 1. [CrossRef]
12. Tran, M.-K.; Akinsanya, M.; Panchal, S.; Fraser, R.; Fowler, M. Design of a hybrid electric vehicle powertrain for performance optimization considering various powertrain components and configurations. *Vehicles* **2021**, *3*, 20–32. [CrossRef]
13. Lai, C.S.; Jia, Y.; Dong, Z.; Wang, D.; Tao, Y.; Lai, Q.H.; Wong, R.T.K.; Zobaa, A.F.; Wu, R.; Lai, L.L. A review of technical standards for smart cities. *Clean Technol.* **2020**, *2*, 290–310. [CrossRef]
14. Husain, I. *Electric and Hybrid Vehicles Design Fundamentals*, 2nd ed.; CRC Press Taylor & Francis Group: Boca Raton, FL, USA, 2011.
15. 2014 BMW I3 Electric Car: Why California Set Range Requirements Engine Limits. Available online: https://www.greencarreports.com/news/1087888_2014-bmw-i3-electric-car-why-california-set-range-requirements-engine-limits (accessed on 22 June 2020).
16. Andwari, A.M.; Pesiridis, A.; Rajoo, S.; Martinez-Botas, R.; Esfahanian, V. A review of battery electric vehicle technology and readiness levels. *Renew. Sustain. Energy Rev.* **2017**, *78*, 414–430. [CrossRef]
17. Friedl, H.; Friedl, G.; Hubmann, C.; Sorger, H.; Teuschl, G.; Martin, C. Range Extender Technology for Electric Vehicles. In Proceedings of the 2018 5th International Conference on Electric Vehicular Technology, Surakarta, Indonesia, 30–31 October 2018. [CrossRef]
18. Heron, A.; Reinderknecht, F. Comparison of Range Extender Technologies for Battery Electric Vehicles. In Proceedings of the 2013 8th International Conference and Exhibition on Ecological Vehicles and Renewable Energies, Stuttgart, Germany, 27–30 March 2013. [CrossRef]
19. Ozsoysal, O.A. Effects of combustion efficiency on an Otto cycle. *Int. J. Exergy* **2010**, *7*, 232–242. [CrossRef]
20. Feng, R.; Li, Y.; Yang, J.; Fu, J.; Zhang, D.; Zheng, G. Investigations of Atkinson cycle converted from conventional Otto cycle gasoline engine. *SAE Tech. Pap. Ser.* **2016**, *1*, 1–10. [CrossRef]
21. Ebrahimi, R. Performance of an irreversible Diesel cycle under variable stroke length and compression ratio. *J. Am. Sci.* **2010**, *6*, 58–64. [CrossRef]
22. Chen, Y.; Ma, J.; Han, B.; Zhang, P.; Hua, H.; Chen, H.; Su, X. Emissions of automobiles fueled with alternative fuels based on engine technology: A review. *J. Traffic Transp. Eng.* **2018**, *5*, 318–334. [CrossRef]
23. Platt, S.M.; El Haddad, I.; Pieber, S.M.; Zardini, A.A.; Suarez-Bertoa, R.; Clairotte, M.; Daellenbach, K.R.; Huang, R.-J.; Slowik, J.G.; Hellebust, S.; et al. Gasoline cars produce more carbonaceous particulate matter than modern filter-equipped diesel cars. *Sci. Rep.* **2017**, *7*, 4926. [CrossRef]
24. Szybist, J.; Wagner, R.; Curran, S. *Internal Combustion Engines for Hybrid Electric Configurations*; National Transportation Research Center: Knoxville, TN, USA, 2017.

25. Tomaszewska, A.; Chu, Z.; Feng, X.; O'Kane, S.; Liu, X.; Chen, J.; Ji, C.; Endler, E.; Li, R.; Liu, L.; et al. Lithium-ion battery fast charging: A review. *eTransportation* **2019**, *1*, 1–28. [CrossRef]
26. Keil, P.; Jossen, A. Aging of Lithium-Ion batteries in electric vehicles: Impact of regenerative braking. *World Electr. Veh. J.* **2015**, *7*, 41–51. [CrossRef]
27. Borghi, M.; Mattarelli, E.; Muscoloni, J.; Rinaldini, C.A.; Savioli, T.; Zardin, B. Design and experimental development of a compact and efficient range extender engine. *Appl. Energy* **2017**, *202*, 507–526. [CrossRef]
28. Solouk, A.; Tripp, J.; Shakiba-Herfeh, M.; Shahbakhti, M. Fuel consumption assessment of a multi-mode low temperature combustion engine as range extender for an electric vehicle. *Energy Convers. Manag.* **2017**, *148*, 1478–1496. [CrossRef]
29. Spectrum "Powertrain Electrification". FEV. 2018. Available online: https://www.fev.com/fileadmin/user_upload/Media/Spectrum/en/Spectrum_64_EN_WEB.pdf (accessed on 3 July 2020).
30. Spectrum "Zero Emission Strategies". FEV. 2017. Available online: https://www.fev.com/fileadmin/user_upload/Media/Spectrum/en/Spectrum_61_EN.pdf (accessed on 3 July 2020).
31. MAHLE Powertrain. MAHLE Range Extender Demonstrator Vehicle. 2017. Available online: https://www.mahle-powertrain.com/media/mahle-powertrain/news-and-press/brochures/range_extender/mahle-powertrain-range-extender-vehicle.pdf (accessed on 3 July 2020).
32. Green Car Congress. Available online: https://www.greencarcongress.com/2019/09/20190910-mahle.html (accessed on 3 July 2020).
33. Guo, C.; Zuo, Z.; Feng, H.; Jia, B.; Roskilly, T. Review of recent advances of free-piston internal combustion engine linear generator. *Appl. Energy* **2020**, *269*, 115084. [CrossRef]
34. Kock, F.; Haag, J.; Friedrich, H.E. The free piston linear generator-development of an innovative, compact, highly efficient range-extender module. *SAE Tech. Pap. Ser.* **2013**. [CrossRef]
35. Hung, N.B.; Lim, O. A review of free-piston linear engines. *Appl. Energy* **2016**, *178*, 78–97. [CrossRef]
36. Jia, B.; Smallbone, A.; Zuo, Z.; Feng, H.; Roskilly, A.P. Design and simulation of a two- or four-stroke free-piston engine generator for range extender applications. *Energy Convers. Manag.* **2016**, *111*, 289–298. [CrossRef]
37. Xu, Y.; Xue, X.; Wang, Y.; Ai, M. Performance characteristics of compressed air-driven free-piston linear generator (FPLG) system—A simulation study. *Appl. Therm. Eng.* **2019**, *160*, 114013. [CrossRef]
38. Mikalsen, R.; Roskilly, A.P. The design and simulation of a two-stroke free-piston compression ignition engine for electrical power generation. *Appl. Therm. Eng.* **2008**, *28*, 589–600. [CrossRef]
39. Rathore, S.; Mishra, S.; Paswan, M.K. Review on Design and Development of Free Piston Linear Generators in Hybrid Vehicles. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Greater Noida, India, 3–5 May 2019; Volume 691, p. 012053. [CrossRef]
40. Jensen, H.-C.B.; Schaltz, E.; Koustrup, P.S.; Andreasen, S.J.; Kaer, S.K. Evaluation of fuel-cell range extender impact on hybrid electrical vehicle performance. *IEEE Trans. Veh. Technol.* **2012**, *62*, 50–60. [CrossRef]
41. Mahapatra, M.K.; Singh, P. Fuel cells. *Future Energy* **2014**, 511–547. [CrossRef]
42. Fuel Cell Today. Available online: http://www.fuelcelltoday.com/history (accessed on 12 July 2020).
43. Kreuer, K.-D. (Ed.) *Fuel Cells: Selected Entries from the Encyclopedia of Sustainability Science and Technology*; Springer: New York, NY, USA, 2013. [CrossRef]
44. Janssen, L.J.J. Hydrogen fuel cells for cars and buses. *J. Appl. Electrochem.* **2007**, *37*, 1383–1387. [CrossRef]
45. Dell, R.M.; Moseley, P.T.; Rand, D.A.J. Hydrogen, fuel cells and fuel cell vehicles. In *Towards Sustainable Road Transport*; Academic Press: London, UK, 2014; pp. 260–295. [CrossRef]
46. U.S. Department of Energy. Available online: https://www.energy.gov/sites/prod/files/2015/11/f27/fcto_fuel_cells_fact_sheet.pdf (accessed on 12 July 2020).
47. Minnehan, J.J.; Pratt, J.W. *Practical Application Limits of Fuel Cells and Batteries for Zero Emission Vessels*; SANDIA Report: SAND2017-12665; Sandia National Lab. (SNL-NM): Albuquerque, NM, USA, 2017. [CrossRef]
48. Udomsilp, D.; Rechberger, J.; Neubauer, R.; Bischof, C.; Thaler, F.; Schafbauer, W.; Menzler, N.H.; De Haart, L.G.; Nenning, A.; Opitz, A.K.; et al. Metal-supported solid oxide fuel cells with exceptionally high power density for range extender systems. *Cell Rep. Phys. Sci.* **2020**, *1*, 100072. [CrossRef]
49. Wu, X.-L.; Xu, Y.-W.; Zhao, D.-Q.; Zhong, X.-B.; Li, D.; Jiang, J.; Deng, Z.; Fu, X.; Li, X. Extended-range electric vehicle-oriented thermoelectric surge control of a solid oxide fuel cell system. *Appl. Energy* **2020**, *263*, 114628. [CrossRef]
50. Wang, J. Barriers of scaling-up fuel cells: Cost, durability and reliability. *Energy* **2015**, *80*, 509–521. [CrossRef]
51. Geng, C.; Jin, X.; Zhang, X. Simulation research on a novel control strategy for fuel cell extended-range vehicles. *Int. J. Hydrog. Energy* **2019**, *44*, 408–420. [CrossRef]
52. Liu, Y.; Li, J.; Chen, Z.; Qin, D.; Zhang, Y. Research on a multi-objective hierarchical prediction energy management strategy for range extended fuel cell vehicles. *J. Power Sources* **2019**, *429*, 55–66. [CrossRef]
53. Álvarez Fernández, R.; Corbera Caraballo, S.; Beltrán Cilleruelo, F.; Lozano, J.A. Fuel optimization strategy for hydrogen fuel cell range extender vehicles applying genetic algorithms. *Renew. Sustain. Energy Rev.* **2018**, *81*, 655–668. [CrossRef]
54. Dimitrova, Z.; Maréchal, F. Environomic design for electric vehicles with an integrated solid oxide fuel cell (SOFC) unit as a range extender. *Renew. Energy* **2017**, *112*, 124–142. [CrossRef]

55. Fernández, R.Á.; Cilleruelo, F.B.; Martínez, I.V. A new approach to battery powered electric vehicles: A hydrogen fuel-cell-based range extender system. *Int. J. Hydrog. Energy* **2016**, *41*, 4808–4819. [CrossRef]
56. Kaparaju, P.; Rintala, J. Generation of heat and power from biogas for stationary applications: Boilers, gas engines and turbines, combined heat and power (CHP) plants and fuel cells. In *The Biogas Handbook: Science, Production and Applications*; Wellinger, A., Murphy, J., Baxter, D., Eds.; Woodhead Publishing: Cambridge, UK, 2013; pp. 404–427.
57. Ji, F.; Zhang, X.; Du, F.; Ding, S.; Zhao, Y.; Xu, Z.; Wang, Y.; Zhou, Y. Experimental and numerical investigation on micro gas turbine as a range extender for electric vehicle. *Appl. Therm. Eng.* **2020**, *173*, 115236. [CrossRef]
58. do Nascimento, M.A.R.; de Oliveira Rodrigues, L.; dos Santos, E.C.; Batista Gomes, E.E.; Goulart Dias, F.L.; Gutierrez Velasques, E.I.; Carrillo, R.A.M. Micro gas turbine engine: A review. In *Progress in Gas Turbine Performance*; IntechOpen: London, UK, 2013; pp. 107–141. [CrossRef]
59. Boukhanouf, R. Small combined heat and power (CHP) systems for commercial buildings and institutions. In *Small and Micro Combined Heat and Power (CHP) Systems: Advanced Design, Performance, Materials and Applications*; Woodhead Publishing: Cambridge, UK, 2011; Volume 15, pp. 365–394. [CrossRef]
60. Ribau, J.; Silva, C.; Brito, F.P.; Martins, J. Analysis of four-stroke, Wankel, and microturbine based range extenders for electric vehicles. *Energy Convers. Manag.* **2012**, *58*, 120–133. [CrossRef]
61. Shah, R.; McGordon, A.; Amor-Segan, M. Micro Gas Turbine range extender—Validation for automotive applications. In Proceedings of the IET Hybrid and Electric Vehicles Conference, London, UK, 6–7 November 2013. [CrossRef]
62. Karvountzis-Kontakiotis, A.; Andwari, A.M.; Pesyridis, A.; Russo, S.; Tuccillo, R.; Esfahanian, V. Application of micro gas turbine in range-extended electric vehicles. *Energy* **2018**, *147*, 351–361. [CrossRef]
63. Tan, F.; Chiong, M.; Rajoo, S.; Romagnoli, A.; Palenschat, T.; Martinez-Botas, R. Analytical and experimental study of micro gas turbine as range extender for electric vehicles in Asian cities. *Energy Procedia* **2017**, *143*, 53–60. [CrossRef]
64. Tran, M.-K.; Sherman, S.; Samadani, E.; Vrolyk, R.; Wong, D.; Lowery, M.; Fowler, M. Environmental and economic benefits of a battery electric vehicle powertrain with a zinc-air range extender in the transition to electric vehicles. *Vehicles* **2020**, *2*, 398–412. [CrossRef]
65. Zhang, J.; Zhou, Q.; Tang, Y.; Zhang, L.; Li, Y. Zinc–air batteries: Are they ready for prime time? *Chem. Sci.* **2019**, *10*, 8924–8929. [CrossRef]
66. Sherman, S.B.; Cano, Z.P.; Fowler, M.; Chen, Z. Range-extending Zinc-air battery for electric vehicle. *AIMS Energy* **2018**, *6*, 121–145. [CrossRef]
67. Gilligan, G.E.; Qu, D. *Advances for Medium and Large-Scale Energy Storage*; Woodhead Publishing: Cambridge, UK, 2015; pp. 441–461. [CrossRef]
68. Cano, Z.P.; Banham, D.; Ye, S.; Hintennach, A.; Lu, J.; Fowler, M.; Chen, Z. Batteries and fuel cells for emerging electric vehicle markets. *Nat. Energy* **2018**, *3*, 279. [CrossRef]
69. Catton, J.; Wang, C.; Sherman, S.; Fowler, M.; Fraser, R. Extended range electric vehicle powertrain simulation, and comparison with consideration of fuel cell and metal-air battery. *SAE Tech. Pap. Ser.* **2017**, *1*. [CrossRef]
70. Eckl, R.; Burda, P.; Foerg, A.; Finke, H.; Lienkamp, M. Alternative range extender for electric cars—Zinc air batteries. In *Conference on Future Automotive Technology*; Springer: Fachmedien Wiesbaden, Germany, 2013; pp. 3–18. [CrossRef]
71. Ghosh, A. Possibilities and challenges for the inclusion of the electric vehicle (EV) to reduce the carbon footprint in the transport sector: A review. *Energies* **2020**, *13*, 2602. [CrossRef]
72. Guanetti, J.; Formentin, S.; Savaresi, S.M. Energy management system for an electric vehicle with a rental range extender: A least costly approach. *IEEE Trans. Intell. Transp. Syst.* **2016**, *17*, 3022–3034. [CrossRef]
73. Krithika, V.; Subramani, C. A comprehensive review on choice of hybrid vehicles and power converters, control strategies for hybrid electric vehicles. *Int. J. Energy Res.* **2017**, *42*, 1789–1812. [CrossRef]