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To cite this article: C Iclodean *et al* 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **252** 012058

IOP Conf. Series: Materials Science and Engineering **252** (2017) 012058 doi:10.1088/1757-899X/252/1/012058

# Comparison of Different Battery Types for Electric Vehicles

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**Abstract**. Battery powered Electric Vehicles are starting to play a significant role in today's automotive industry. There are many types of batteries found in the construction of today's Electric Vehicles, being hard to decide which one fulfils best all the most important characteristics, from different viewpoints, such as energy storage efficiency, constructive characteristics, cost price, safety and utilization life. This study presents the autonomy of an Electric Vehicle that utilizes four different types of batteries: Lithium Ion (Li-Ion), Molten Salt ($Na\text{-}NiCl_2$), Nickel Metal Hydride (Ni-MH) and Lithium Sulphur (Li-S), all of them having the same electric energy storage capacity. The novelty of this scientific work is the implementation of four different types of batteries for Electric Vehicles on the same model to evaluate the vehicle's autonomy and the efficiency of these battery types on a driving cycle, in real time, digitized by computer simulation.

## 1. Introduction

Due to high demand of fossil fuels on the international markets together with the aggravation of environment problems caused by an increased number of internal combustion engine vehicles, there is an increased interest in the research and development of batteries used in electric and hybrid vehicles. These vehicles represent a solution for the future in road transportation field, taking into consideration the interest in reducing greenhouse gas emissions, as well as air and sound pollution [1, 2].

According to [3], transportation sector represents one of the main determinant factors of climatic changes, 23 % of the greenhouse gas from the atmosphere coming from this sector, being second in this classification after the industrial sector. Due to this reason, in 2015, "Paris declaration on Electro-Mobility and Climate Change and Call to Action" has been adopted. This declaration has as a main objective reducing global warming with more than 2 degrees. This goal is achievable if electric vehicles represent 35 % from the total number of vehicles sold until 2030.

In order to reach this target, a decrease in the acquisition price of the electric vehicles is mandatory until it reaches a level closer to that of the internal combustion engine vehicles. Nowadays, the most expensive part of an electric vehicle is the battery, which represents 25 … 50 % of the price of the electric vehicle, depending of the technology used [4, 5, 6].

As presented by [5, 7, 8], a decrease of battery cost is anticipated by 2025, reaching a price of 225 Euros/kWh, which will determine a significate decrease in the acquisition price of the electric vehicles, helping them reach a value closer to the price of internal combustion engine vehicles. As presented by [4], production costs of the Li-Ion batteries decreased with over 50 % from 2007 until 2014.

Figure 1 presents a comparative market price evaluation of different electric vehicles, depending on battery capacity:

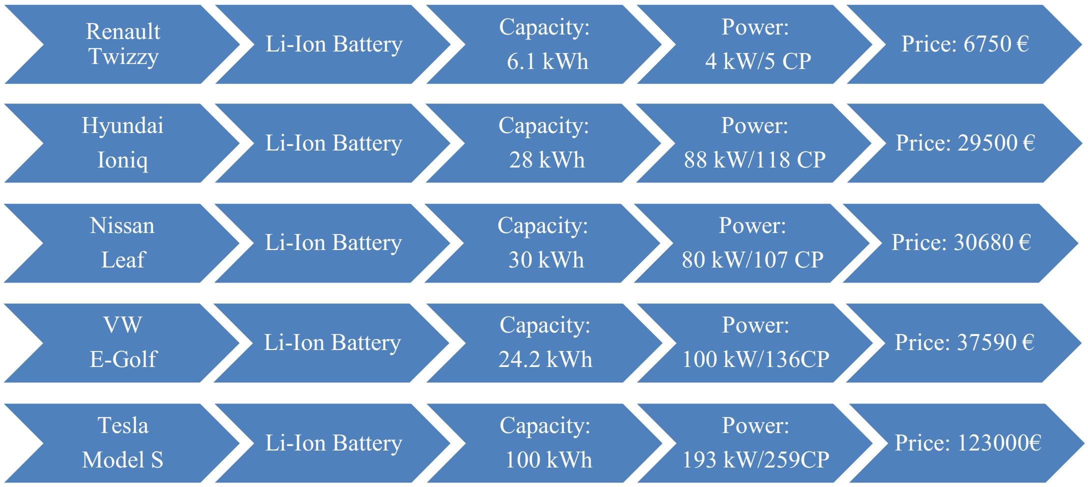


**Figure 1.** Comparative evaluation of different electric vehicle market cost.

Analyzing these types of electric vehicles presented above, according to the studies of [4, 5, 6] an approximate cost for one kWh energy is between 255 € (Nissan Leaf) and 388 € (VW E-Golf), cost calculated at a battery value of 25 % from the total vehicle amount.

As observed in figure 1, Li-Ion batteries are nowadays representing the most used technology in electric vehicles, both thanks to high energy density and increased power per mass battery unit, allowing the development of some types of batteries with reduced weight and dimensions at competitive prices. Trough studies carried out by [8, 9, 10, 11] Li-Ion batteries used in electric vehicle industry were studied, highlighting increased power (800 … 2000 W/kg), and specific energy (100 … 250 Wh/kg), in comparison with Ni-MH batteries.

In accordance with [12] studies, this technology represents the best "charge to weight" solution, fulfilling one of the most important conditions for a battery used in electric vehicle industry, which made an easily replacement of Ni-MH batteries by them. Another advantage is the lack of memory effect (to gradually lose the maximum energy capacity in case of repeatedly recharge, without being totally discharged), resulting an increased life cycle.

The disadvantage of Li-Ion batteries is represented by high developed operational temperature, which could affect energetic performances, among with lifetime and safety in exploitation [13]. This technology requires one management battery system in order to control and monitor internal cell temperature. Apart from the disadvantages caused by exploitation temperature, there are also problems related to high production costs [14], recycling capacity of batteries out of use [15] and recharging infrastructure [16].

At the beginning of 2000, Ni-MH batteries represented the most advanced technology used in hybrid and electric vehicles, being considered the first step to achieving the technology used today.

In comparison with the batteries used in those days, namely Ni-Cd and Lead-Acid batteries, Ni-MH technology was meeting the requirements imposed to batteries which were developed in order to be used in automotive industry. The advantages were: high energy density and power, allowing an autonomy of over 300 km while using batteries with 70 Wh/kg specific energy. Moreover, these batteries can be used with success in propulsion systems equipped with electric engines of 320 V AC, or 180 V DC, showing an increased lifecycle (until 80 % Depth of Discharge DOD). Other advantages were: the capability of using regenerative energy recovered from braking, recyclable materials were used in their development, excellent thermal properties (operating temperature starting from – 30 °C up until + 70 °C), battery charging and discharging safety, etc. [17, 18]. From a comparison made by [19] between Li-Ion and Ni-MH batteries, it is shown that, from a cell point of view, Li-Ion cells offer a specific energy increased by 20 %. But, if the whole battery system is taken into account, with the added mass of battery management system in the Li-Ion technology, it can be said that the management system of the Ni-MH battery is simpler, with reduced weight. If we compare the electric Nissan Leaf EV, equipped with a Li-Ion battery, having an autonomy of 160 km with the electric car of GM, EV1, equipped with Ni-MH battery, having an autonomy of 280 km, it results that Ni-MH batteries are more efficient, from an autonomy point of view. The disadvantages of Ni-MH batteries are increased weight and obsolete technology. Researches conducted in the last years in the field of electric vehicles battery technology have met an advancement by developing other battery types among the classic Ni-MH batteries.

Na-$NiCl_2$ batteries, also known as ZEBRA batteries, (Zeolite Battery Research Africa) were used for equipping some concept cars and buses used in urban public transportation [20]. These types of batteries are remarkable especially for their increased energy density (90 … 120 WH/kg), and also due to lower price, compared with other existing technologies. Other advantages are: overcharge and over discharge resistance, increased cycle life, and constructive robustness, which permits their utilization in harsh environments, their performances not being affected by low temperatures.

The big downsize of the Na-$NiCl_2$ batteries it's represented by increased internal operating temperatures (270 °C … 350 °C), continuous utilization of the electric vehicle being necessary in order to avoid freezing the battery electrolyte. In case the car is not used, maintaining the system at the operating temperature can be possible through an external heating system, which consumes 90 Wh power from the battery. In contrast, 12 to 15 hours are needed in order to defrost the battery and to bring it back to its functional parameters [21].

Although Li-Ion batteries are now in an advanced development stage, close to the theoretical values obtained through researches [22, 23], this type of battery cannot yet satisfy requests regarding especially the autonomy, making it necessary to find new technologies which can offer a high storage energy capacity, among with an extended lifespan [24]. Another type of technology, namely the Li-S battery, has showed a lot of interest from researchers mostly due to increased theoretical specific energy (2500 Wh/kg), among with its theoretical specific capacity (1672 mAh/kg), thus being considerate a strong competitor for the technology used today, representing a viable solution in the development of future electric vehicles. At the moment, due to reduced lifespan and energy retention capacity, the use of this battery type is limited [25, 26].

## 2. Materials and Methods

In this paper a virtual electric vehicle, based on the constructive parameters of the electric VW E-Golf was developed in AVL Cruise, in order to emphasize autonomy differences and to evaluate the performances of these four types of batteries. On this virtual model, all four battery types will be implemented and then details regarding vehicle autonomy will be studied trough computerized simulation.

### *2.1. Methodology of the simulation process*

The steps used to define the algorithm of the computerized simulation process are presented in figure 2. The first phase consists in developing the model of the virtual electric vehicle in AVL Cruise.

AVL Cruise is a simulation package which has the possibility to simulate a large variety of vehicle propulsion systems, in order to study the evolution of the energy utilized in vehicle propulsion, starting from one energy source (electric battery) to one energy consumer (transmission system). A preprocessing tool is used to enter initial and input data, as well as technical characteristics of the new simulation model. After the assembly of the vehicle parts, along with supplementary systems, the software analyzes and calculates all processes requested during simulation time, with the help of all mathematical equations and computational algorithms used behind the Graphical User Interface [27].

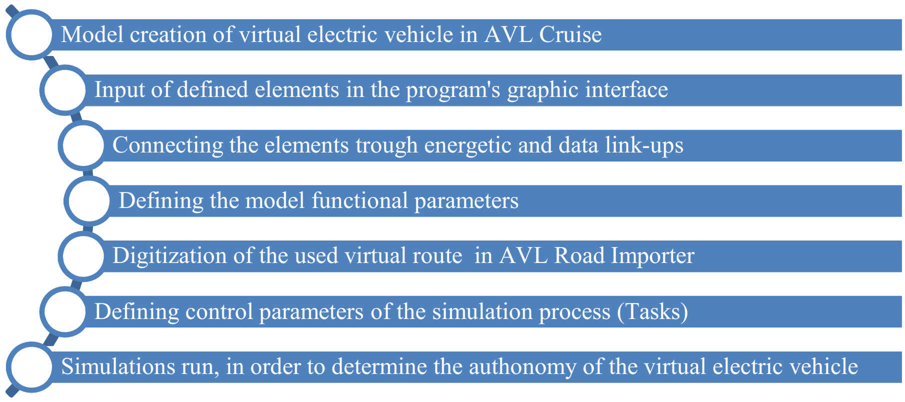


**Figure 2.** Steps of the computerized simulation process algorithm

### *2.2. Virtual model of the electric vehicle*

In order to simulate the functioning of an electric vehicle, one virtual model of the VW E-Golf was created and developed in AVL Cruise (figure 3). Constructive data were taken from manufacturer's technical documentation in the interest of developing this virtual model [28, 29].

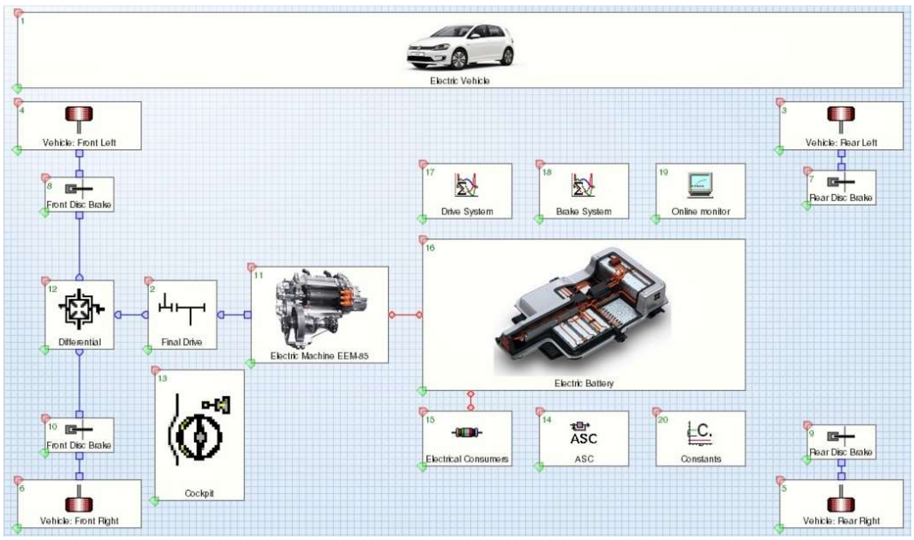


**Figure 3.** Virtual model of the studied electric vehicle in AVL Cruise

The elements of the model are the following: Electric Vehicle (1), Final Drive (2), Vehicle Wheel Rear Left (3), Vehicle Wheel Front Left (4), Vehicle Wheel Front Right (5), Vehicle Wheel Rear Right (6), Rear Disk Brake (7), Front Disk Brake (8), Rear Disk Brake (9), Front Disk Brake (10), Electric Machine (11), Differential (12), Cockpit (13), ASC Control (14), Electrical Consumers (15), Electric Battery (16), Drive System (17), Brake System (18), Online Monitor (19) and Constants (20). The informational connections are made through Data Bus Connection.

The Electric Vehicle component (1) contains general data, such as: constructive parameters, aerodynamic features, etc. [30, 31]. The Final Drive element (2) is used as a link in the transmission of the cinematic chain before the differential. The Wheel (3 ... 6) takes into consideration many variables and their influence and effect on the rolling state. All input data for all vehicle's wheels is identical. The Brake component (7 ... 10) defines the characteristics of the braking elements. The E-Machine component (11) defines general data of the electric machine (table 1). For calculating power losses, Maximum Power (Torque) (figure 4) and Efficiency Maps (figure 5) are defined [32].

**Table 1.** General data of the Electric Machine.

| Name | Value | Unit |
|---|---|---|
| Type of Machine | PSM | - |
| Characteristic Maps and Curves | Overall | - |
| Nominal Voltage | 323 | V |
| Inertia Moment | 1.0e-4 | kg*m$^2$ |
| Maximum Speed – motor related | 12000 | 1/min |
| Maximum Power – motor related | 85 | kW |
| Maximum Torque – motor related | 270 | Nm |
| Maximum Speed – generator related | 7000 | 1/min |
| Maximum Power – generator related | 84 | kW |
| Maximum Torque – generator related | 264 | Nm |
| Maximum Efficiency | 92.5 | % |
| Initial Temperature | 20 | ° C |

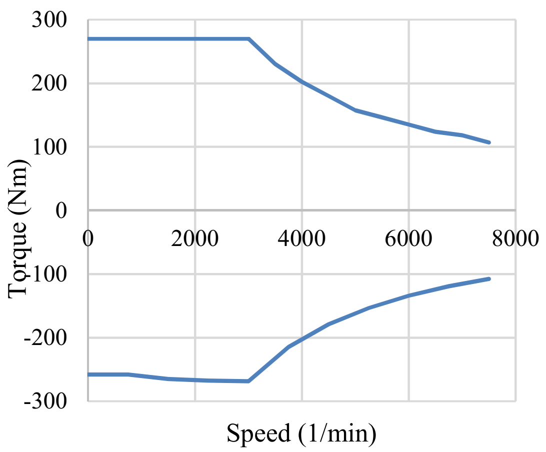


**Figure 4.** Electric Machine Torque Map

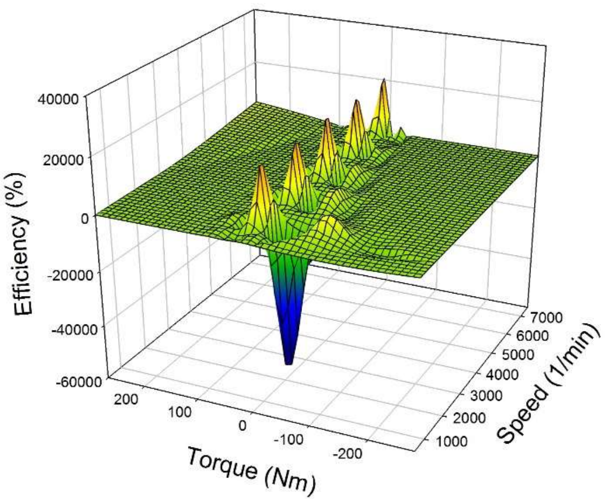


**Figure 5.** Electric Machine Efficiency Map

The Differential unit (12) compensates for discrepancies in the respective rotation rates of the drive wheels, allowing different wheel speed during cornering. The Cockpit (13) links the driver and the vehicle, connections being made only via Data Bus.

Anti-Slip Control component (14) controls the coefficient of friction of the single wheels, by checking the force transmission factor (ratio between the force which should be transmitted and maximum transmittable force) of all connected wheels (driven wheels).

The Electrical Consumers (15) are all the consumers of the electric vehicle network. In the modelling process, they are the ohmic resistors in the onboard network, which represents an electric current loss.

The Electric Battery component (16) simulates the battery used in the power supply of the electric vehicle. The electrical characteristics of all four battery types studied in this paper are presented in table 2 [32, 33, 34, 35, 36, 37, 38, 39, 40].

The Drive System (17) is a function defined by the user in C-Code, used to simulate the engine control unit, both in engine and generator mode. The Brake System (18) is a function defined by user in C-Code for controlling the conversion of the motor moment in braking pressure. The Monitor element (19) has the role of monitoring specific signals of the Data Bus Connection. The Constants component (20) allows the user to define all the constant values used by the elements of the electric vehicle trough Data Bus Connection [32].

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**Table 2.** General parameters of the Electric Battery component.

| Name | Value for Battery Type | | | | Unit |
|---|---|---|---|---|---|
| | Li-Ion | Na-NiCl$_2$ | Ni-MH | Li-S | |
| Maximum Charge | 75 | 84 | 85 | 80 | Ah |
| Nominal Voltage | 323 | 289 | 288 | 305 | V |
| Stored Energy | 24.2 | 24.2 | 24.2 | 24.2 | kWh |
| Maximum Voltage / Minimum Voltage | 339 / 308 | 275 / 304 | 274 / 302 | 290 / 320 | V |
| Initial Charge | 100 | 100 | 100 | 100 | % |
| Number of Cells per Cell-Row | 12 | 12 | 20 | 26 | - |
| Number of Cell-Row | 17 | 30 | 20 | 1 | - |
| Internal Resistance charge/discharge | 1 / 1 | 1 / 1 | 1 / 1 | 1 / 1 | Ω |
| Operating Temperature | 33 | 270 | 36 | 30 | °C |
| Specific Heat Transition | 0.4 | 6 | 0.4 | 0.08 | W/K |
| Specific Heat Capacity | 795 | 950 | 677 | 1650 | J/kg*K |
| Mass of Battery | 318 | 457 | 534 | 173 | kg |
| Battery Price | 300 | 500 | 400 | 250 | € |

### 2.3. *Digitized infrastructure of the virtual road*

A Virtual Road is a representation obtained through computerized digitization of one real road sector, generated by AVL Road Importer, based on the coordinates taken from a software platform that shows in detail the terrestrial surface (Google Earth). It has an altitude profile which is punctually implemented with the GPS Prune application that uses GPS coordinates, which represent the Latitude, Longitude and Height of the reference points.

In order to evaluate the autonomy of the electric vehicle in AVL Cruise, the Nardo circuit from Italy was used as a virtual road (figure 6). This circuit with a length of 12.6 km is a testing track for vehicles and due to its circular geometry, it allows the displacement of the virtual vehicle in a closed loop until it reaches the maximum battery autonomy. Defining the geometry of the route was accomplished through a sequence of parametrized segments, which follow the altitude gradient of the real track.


**Figure 6.** Nardo Ring, Nardo, Italy

In order to digitize the virtual track, the Keyhole Markup Language (KML) file from the Google Earth application was imported. This file contains all data used in the digitization of the road. They were introduced as initial data in the GPS Prune tool, which afterwards added punctually the altitude values for each GPS coordinates set, both for latitude and longitude.

The obtained virtual road was afterwards exported in a compatible format with AVL Cruise application, and was multiplied by 20 times in order to realize a closed loop circuit. This therefore was loaded in the Cycle Run section and afterwards used in the definition of the tasks of the simulations. The calculation tasks contain information regarding environment conditions, traveled distance, speed limits, driving time, behavior of the driver, etc. [27].

## 3. Results and Discussions

The results of the four battery types obtained from AVL Cruise simulations are presented in table 3.

**Table 3.** AVL Cruise simulations results.

| Name | Value for Battery Type | | | | Unit |
|---|---|---|---|---|---|
| | Li-Ion | Na-NiCl$_2$ | Ni-MH | Li-S | |
| Electrical Consumption (VW Data) | 12.7 | - | - | - | kWh/100km |
| Electrical Consumption (Real Test Drive) | 18.2 | - | - | - | kWh/100km |
| Electrical Consumption (AVL Cruise) | 14.7 | 12.6 | 15.8 | 17.2 | kWh/100km |
| Electrical Vehicle Autonomy (VW Data) | 190 | - | - | - | km |
| Electrical Vehicle Autonomy (Real Test Drive) | 130 - 190 | - | - | - | km |
| Electrical Vehicle Autonomy (AVL Cruise) | 165 | 192 | 153 | 140 | km |
| Total Output Energy | 6826 | 5927 | 7006 | 7979 | kJ |
| Total Input Energy | 184 | 222 | 184 | 159 | kJ |

The Electrical Consumption (kWh) results, presented in figure 7, were obtained on Nardo Ring (12.6 km), each simulation being done in identical conditions. After analyzing the results, it can be observed that the lowest energy consumption was achieved while using Na-NiCl2 batteries, which helped to develop a maximum autonomy of 192 km, with an average consumption of 12.6 kWh/100 km or 1.59 kWh/lap. Li-Ion batteries achieved a maximum autonomy of 165 km, with an average consumption of 14.7 kWh/100 km or 1.85 kWh/lap. Ni-MH batteries reached a maximum autonomy of 153 km, with an average consumption of 15.8 kWh/100 km, and 1.90 kWh for a lap. The maximum energy consumption was achieved while using Li-S batteries, which helped to develop a maximum autonomy of 140 km, with an average consumption of 17.2 kWh/100 km and 2.17 kWh/lap.

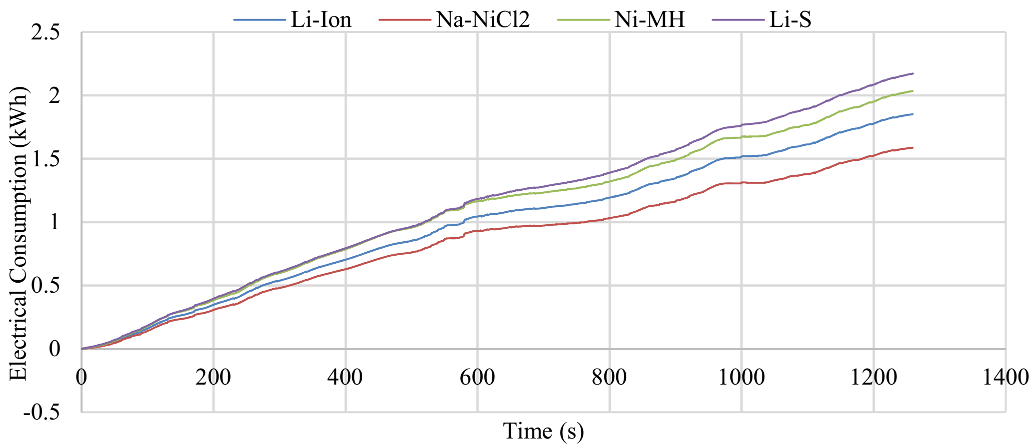


**Figure 7.** Electrical Consumption (Nardo Ring 12.6 km)

The obtained values are validated only for Li-Ion batteries, through official data received from the producer of the electric vehicle, and through data obtained from testing the vehicle in real traffic conditions. The results of the other battery types were obtained only through computerized simulation, of a model validated based on real data, without being validated through experimental measuring.

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Total Output Energy (kJ) and Total Input Energy (kJ) results obtained for each simulation, with all the four battery types, are presented in figure 8. The results' analysis reveals that the recovered energy represents between 2 and 4 % of the total consumed energy. The total amount of energy obtained from recovery braking depends on the altitude profile, but also on the instant storage capacity of each battery type, which may lead to different results.

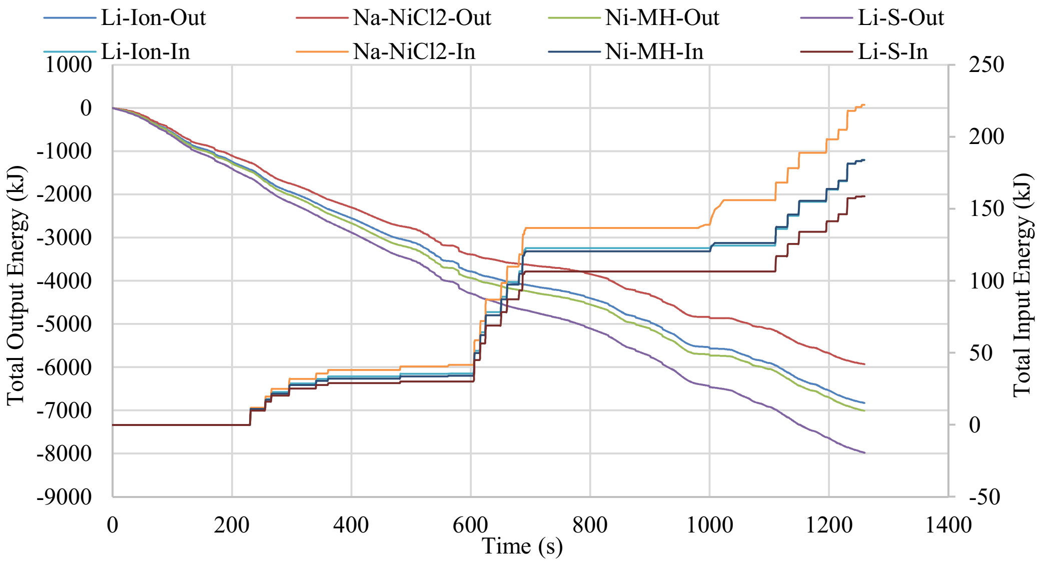


**Figure 8.** Total Output Energy and Total Input Energy

The Electrical Power (kW) results, obtained after each simulation, are presented in figure 9. The power developed by the electric engine (identical in all four cases) is similar for all four battery types, significant differences only occur while changing the operating mode of the electric engine depending on the altitude profile of the route. Compared to the power values developed by the electric engine powered by a Li-Ion battery, the Li-S batteries generate 0.5 % less power, $Na\text{-}NiCl_2$ generate 0.5 % more power, and Ni-MH batteries generate 1.3 % more power.

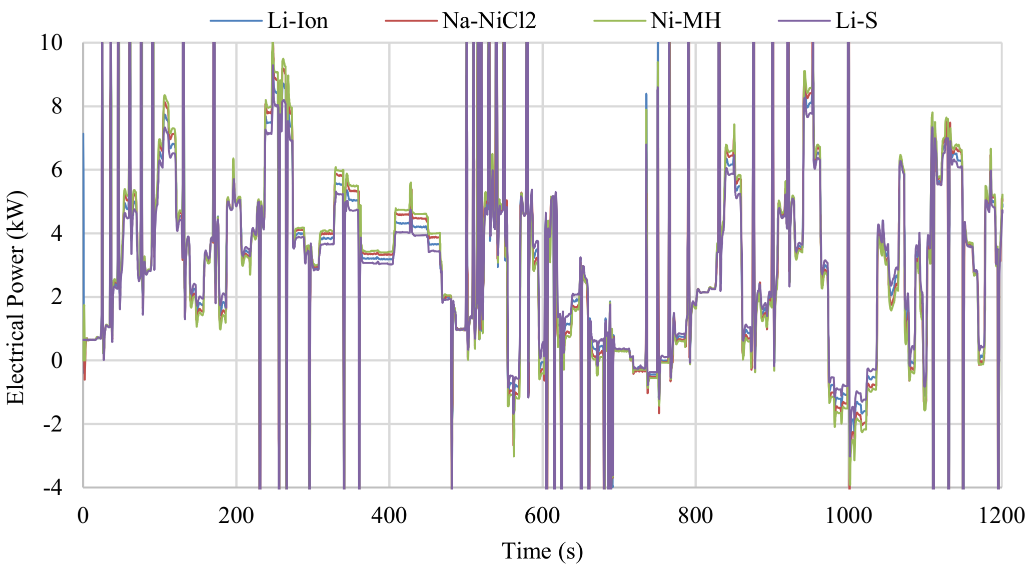


**Figure 9.** Electrical Power

## 4. Conclusions

Na-NiCl2 batteries have proven to be the best choice from an energy consumption point of view (12.6 kWh/100 km). Besides that, other important advantages are their low price, increased lifecycle or great functioning under normal parameters in harsh environments. One disadvantage of these batteries is increased operating temperature, which is causing the battery electrolyte to solidify if the vehicle is not used. That is why, it is necessary to have one external system which maintains the battery's operating temperature under functional parameters.

According to these conducted studies, it has been demonstrated that the highest energy consumption (17.2 kWh/100 km) is accomplished by Li-S batteries. However due to their low weight, increased energy storage capacity and low price, compared to other battery technologies, they might be one of the best solutions for systems with high energy storage capacity.

Ni-MH batteries, despite having a reasonable energy consumption, (15.7 kWh/100 km) they are inefficient, having an increased energy density and power, heavy weight as well as an outdated technology.

Nowadays, Li-Ion batteries have the biggest market segment in equipping electric vehicles. Moderate energy consumption (14.7 kWh/100 km), continuous decline of the cost price, advanced manufacturing technology, increased cycle life, low weight and high energy storage potential make Li-Ion batteries an optimal choice in this field. Their disadvantage is represented by high functioning temperatures, which may have negative effects on their energetic performances and lifecycle. All these represent risks regarding safe exploitation of the vehicle.

**Acknowledgment**

The simulations presented in the paper were done using the software AVL Cruise supported by AVL List GmbH, Graz, Austria.

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