COMPARATIVE SIMULATION ANALYSES ON ENERGY FLOW CHARACTERISTICS OF DIFFERENT HEV CONFIGURATIONS

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ABSTRACT

Last five decades, in energy sector, practitioners and researchers give serious importance of the matter of 3E (*E*conomical, *E*fficiency and *E*nvironmentally) that expected from any energy machine. In this case, where automation and intelligent technology are becoming more and more advanced, the vehicles have started to become electrically powered by evolving themselves on the basis of comfort as well as driving dynamism including Hybrid Electric Vehicles. HEV topology consists of three main types as serial (SHEV), parallel (pHEV) and combined (power split). Both serial and parallel configuration; ICE and electrical devices (battery, electric motor/generator) require an energy management strategy for optimum 3E approach. In this study, the energy flow characteristics of PHEV vs SHEV were compared with simulation methodology. AVL Cruise is used for modelled and simulated the model HEVs. Modelled PHEV and SHEV is compared each other in terms of energy flow characteristics for under same selected conditions and explained with sankey diagrams.

Keywords:
Hybrid Electric Vehicles
Energy Flow Characteristics
AVL Cruise
Driving Cycles
PHEV, SHEV

1. INTRODUCTION

In the energy sector, every product and its outputs have to being preferable due to the criteria's of efficient, economical and environmentally friendly. One of the main actors of today's energy consumption is undoubtedly the transportation sector. Automotive manufacturers take into consideration among the main factors when producing vehicles can be firstly listed as; maximum fuel economy, minimum emission pollutions, optimum energy usage and good driving dynamics. Last three decades, electrification of the vehicles is playing a respectable role in automotive market. Environmental factors and the increasing costs of fossil fuels are the most important predictors of the formation of this phenomenon. Reduction of dependence on fossil fuels, producers continue to develop alternative energy sourced vehicles. Zero emission vehicles (full electric (EV) and fuel cell powered (FCV)) and low emission hybrid vehicles (hybrid electric vehicles (HEV), plug-in HEVs (PHEV), rage extended HEVs) are being produced and used increasingly to serve this purpose.

Basically, hybrid vehicle is defined as; a vehicle that used two or more different power sources for start-up [1]. Regeneration of technological assessments bringing up to HEVs for a good structure like a bridge between conventional internal combustion engines (ICEs) to EVs. Although production costs are still high; HEVs, both minimize fuel consumption (with the helped of regenerative breaking and second power source) and emission pollution of ICEs and compensated the disadvantages of EVs due to lack of range and infrastructure. Figure 1 illustrated an example of working principle of HEVs. [2]

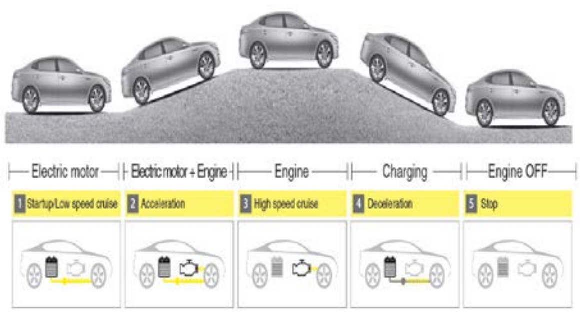

Fig. 1. Working principle of HEVs [17]

HEVs include more electrical devices compared to ICEs such as electric machines/generators (EM/G), energy storage battery, power electronics, controllers, and energy converters, etc. [3]. In this case, the energy management systems and vehicle architectures are at the forefront of important issues for HEVs. HEV topology consists of three main types as serial (SHEV), parallel (PHEV) and combined (power split). In this study, the PHEV and SHEV will be compared and discussed. Figure 2 represent the HEVs power flows diagrams with components.

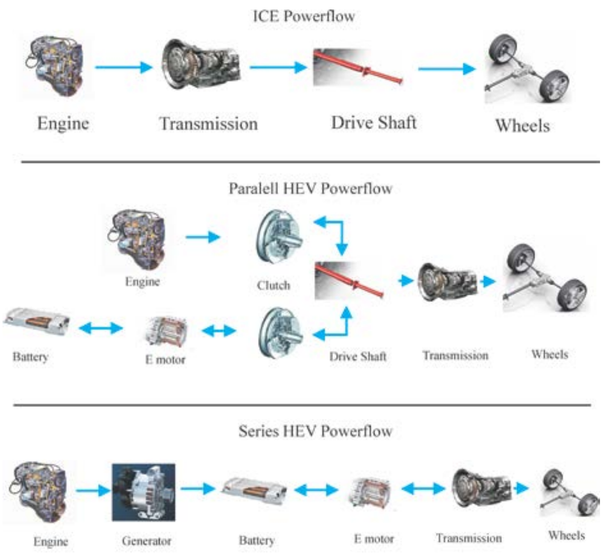

Fig. 2. ICE, PHEV and SHEV power flow diagram

All these electrical systems and the ICE must work together perfectly in order to achieve the optimum energy efficiency. For this, the modelling and control strategies must work without an error. With all of these, the first question before an HEV will produced is which topology should be used in that vehicle? With a simpler approach, which HEV will be chosen for produce if a vehicle has the same size and ICE? In this article, the answer to this question is to be addressed comparatively in terms of energetic approach.

Before the previous studies part of article; given the advantages and disadvantages of PHEV and SHEV will help to make comparison easier. Merits and demerits of PHEV and SHEV are given in Table 1.

Table 1. Merits and demerits of PHEV and SHEV [4].

Arch.	**PHEV**	**SHEV**
Merits	*Higher energy efficient *Less modification *Limited components *All-thermal mode possible	*Good engine dynamics *Higher range in E-mode *Excellent energy recovery in reg. braking *Easy installation and transmission
Demerits	*Larger ICE rage needed *Lower dynamic performance in E-mode *Limited regenerative braking recovery *Complex transmission and coupling	*Lower energy effic. *More components *More mass, volume and cost *All-thermal mode impossible *Larger battery pack

The energy flow characterization is the whole of the analysis showing how efficiently the entire vehicle is used energetically and how and where the energy losses are. With this perspective, [5] simulated the energy flow characteristics of different HEVs with AVL. As concluded, results showed a direct influence of the power train configuration on the behaviour of the energy flow from the EM to the battery. [6] studied a SHEV (bus), for a range-extended assisted and developed by Tsinghua University, analyzed the energy efficiency with two different energy management strategies (CD-CS and blended) using an energy flow chart method. [7] pressed the study under SHEV (bus) too. In paper, series hybrids mentioned as generally preferred for city bus applications due to their frequent stop and go operations. Additionally, the round-trip efficiency of the regenerative braking system was found 27%. [8] studied the different HEVs energy fluctuations under Matlab programming application. Simulation results written for vehicles that utilize hybrid propulsion system consumed 35% less fuel on highway drive and even 60% less fuel in urban drive. [9] studied the control strategies of dynamic programming scale for regenerative braking systems energy flow analyses. Analysis results can be read as the PSR-RB strategy has a similar energy-saving rate as that of the DP strategy, approximately 8% relative to the CDCS strategy. [10] expressed the related study under focusing on the energy efficiency comparison among different power-train configurations. The fuel economy, power component, and energy storage component SOC of the HEV and HHV were obtained through the NEDC simulation. From study results, hydraulic-electric hybrid vehicle provide the best energy cost among all the configurations studied. [11] discussed the 3-step hybrid drive-train design process. As concluded, the maximum of energy recovery efficiency and minimum required generator size varies between 22% - 31% and 13 [kW] - 34 [kW] for vehicle masses between 800 [kg] and 1650 [kg] for NEDC. [12] compared the two different PHEV which donated P1 and P2. In result part, comparative results indicate that the P2 HEV saves about 6.68% fuel consumption over the P1 HEV, while more improvement can be observed from the proposed velocity coupling HEV, with 13.82% fuel consumption reduction over the P1 HEV. [13] prepared a excellent review for modelling and control of HEVs. Detailed control algorithms, system identifications, energy management strategies were given with examples. Besides these, it can be reachable the industrial evolution of HEVs can be found in [13]. [14] simulated the CO_2 reduction with FLC-based hybrid system which is implemented on conventional ICEVs. AVL Cruise was used to calculate CO_2 emission factors of vehicle and four types of vehicle (Gasoline ICE, Diesel ICE, Gasoline HEV, Diesel HEV) simulation models were developed. As result, HEVs given more promising outputs compared the ICEs. [15] analyzed and compared the hybridization effect on the fuel consumption of HEVs. PHEV and SHEV architectures were tested using urban and road driving profile. Reduction in fuel consumption was found with low hybridization levels.

2. METODOLOGY

2.1. Simulation and Vehicle Parameters

"Computer modelling and simulation programs are highly effective and economical tools for use in examining the effects of design alternatives and energy management strategies on hybrid vehicles before construction of a prototype begins"[7]. In this simulation study, AVL Cruise is used for validating and analyzing the differences SHEV and PHEV modelled cars. The modelled vehicles parameters are given in Table 2. One model vehicle with the same weight, same chassis and same ICE, were applied for PHEV and SHEV. Table 2 also shows the other apparatus and features of the tools modelled in terms of being able to analyze as energy flow characteristics with different electrical components and to give an idea with the energetic approach.

Table 2. Modelled HEVs parameters

Component	**PHEV**	**SHEV**
Vehicle and ICE	4-cylinders Spark Ignition engine Displacement: 1460 cm^3 Maximum Power: 86 kw Peek torque: 130 Nm @ 3500 rpm Aerodynamic drag coef.: 0.3 Vehicle frontal area (m^2): 2.15 Rolling friction coef: 0.015 Wheel radius (m): 0.289 Mass: 1310/1620 kg Frontal area: 2,15 m^2 Wheel base: 2690 mm	
Electric Motor	PSM Nominal V= 144V Max.Speed= 8000rpm	PSM Nominal V= 288V Max.Speed= 6000rpm
Transmission	CVT Min/max ratio= 0,5/2.87	SRT Raito=3,095
Battery	Single Cell Max. Charge=6,9 Ah Nominal V= 160 V	NİMH 40 cells Max. Charge=6,5Ah Nominal V= 7.2 V
Generator	-	PSM Nominal V=288V Max.Speed=8000rpm

2.2. Mathematical Models

"The modelling objectives generally determine the accuracy and architecture requirements of a mathematical model, the employed methodology, and the time required to build the model." [16]. The longitudinal vehicle dynamics and the individual drive train components are modeled, following the quasi-static upstream modeling approach of [26].

$$T_v = (f_R M_v g \cos\emptyset + M_v g \sin\emptyset \frac{1}{2} C_D \rho A_v V_v^2) r_w \quad (1)$$

where T_v is vehicle torque, V_v, M, A_v are the speed, mass and frontal area of the vehicle, r_w is the wheel radius, f_R is the rolling resistance (friction) coefficient, C_D and ρ are the drag coefficient and air density, ∅ is the road grade and g is gravitational acceleration. With this consideration, the vehicles traction energy formula is given with eq. 2.

$$E_{trac} = E_{kin} + E_{pot} + E_{roll} + E_{aero} \quad (2)$$

Those, sum of the kinetic, potential, rolling and aerodynamic energies. The total vehicle mass is the sum of the nominal vehicle mass, combustion engine, battery system, and electric machine, i.e.,

$$m_{ve} = m_{ve0} + m_{ce} + m_{ba} + m_{em}. \quad (3)$$

The internal combustion engine model is based on the Willans approximation, i.e. [16] the brake mean effective pressure p_{bmep} is an affine function of the fuel mean effective pressure p_{fmep},

$$p_{\text{bmep}} \approx e(\omega_c) * p_{\text{fmep}} - p_{\text{bmep0}}(\omega_c) \quad (4)$$

where $e(\omega_c)$ is the internal efficiency and $p_{\text{bmep0}}(\omega_c)$ is the drag mean effective pressure.

The engine drag torque (including the inertial torque) is then given by [16] as;

$$T_{ice0} = J_{ice} * \Delta(\omega_c) + \frac{Vd * p\text{bmep0}(\omega c)}{4 * \pi} \quad (5)$$

with the inertia J_{ice} and the displacement V_d.

The EM in the velocity coupling HEV plays two roles under different power demand conditions: as a generator or motor. When operating generator; the generator power P_g is computed by

$$P_g = T_g \eta_g \omega_g \; ; \quad P_m = (T_m \omega_m) / \eta_m \quad (6,7)$$

where, T_g is the generator torque, ω_g is angular speed of generator, and η_g is the efficiency of generator. When operating as a motor, eq. (7) is used for motor torque. As known, EM efficiency is a function of angular speed of motor/generator and torque. Figure 3 is illustrated the typical efficiency of EM. The minus part of motor showed the generator side of permanent magnet synchronous motor (PSM).

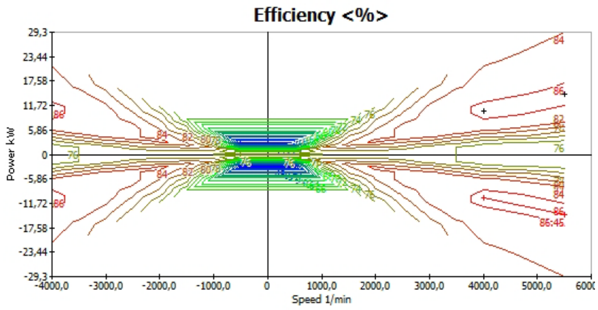

Fig. 3. Typical efficiency of Electric Motor and Generator

The battery pack consists of multiple modules in parallel and in series which are each modeled as a voltage source in series with a resistance. The battery model is based on an AVL model of a 6.9 single cell and 6,9 Ah NiMH battery. Battery model and detailed formulations can be found in [16]. In battery parameter general assumption of formulation is given in eq. 7 and 8. The State of Charge (SOC) and State of Energy (SOE) formulas are presented with eq. 9and 10.

$$P_{batt} = V_{oc} I_{batt} - I^2_{batt} R_{batt} \quad (7)$$

$$Ibatt = \frac{Voc - \sqrt{Voc^2 - 4Rbatt * Pbatt}}{2Rbatt} \quad (8)$$

$$SOC(k+1) = SOC(k) - [(I_{batt} * \Delta t)/Q_c] \quad (9)$$

$$Ebatt = Q_{batt} V_{oc,max} \quad (10)$$

3. RESULTS OF ENERGY FLOW CHARACTERISTICS OF PHEV AND SHEV

In this subsection, energy flow characteristics of PHEV and SHEV were illustrated and explained with the helped of sankey diagrams of mentioned models. First, for the ICE of HEV simulation results were given comparative analyses of the fuel consumption and emission comparison for better comparison. In figure 4., the fuel consumption and engine speed depends on time, under UDC driving cycle is figured for a) PHEV and b) SHEV.

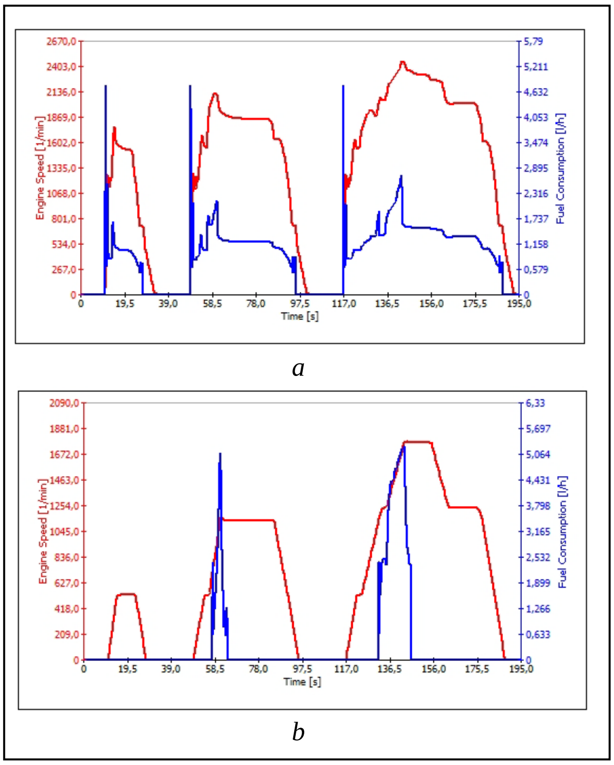

Fig. 4. Fuel consumption of PHEV and SHEV

Total fuel consumption (FC), CO, NO_x and HC emissions under UDC cycle are showed in Table 3. From this point of view; SHEV is more preferable outputs results when compared with PHEV except NO_x values.

Table 3. Emission comparisons of PHEV and SHEV

Architect.	**FC** *l/100km*	**CO_2** *g/km*	**NO_x** *g*	**CO** *g*	**HC** *g*
PHEV	4,63	105,2	0,45	2,98	0,36
SHEV	3,879	83,370	0,68	1,36	0,20

The main goal of this study is compared of different HEVs with the basis of energy flow characteristics. In systematic view; the models predict the instantaneous energy losses with the addition of sankey diagrams.

In figure 5, the PHEV (a) and SHEV (b) energy flow characteristics were illustrated under certain conditions. Because the model vehicles use automatic gearshifts (AMT with SRT for SHEV and CVT for PHEV) in both, the system energy flow is compared by showing the battery and the electric motor during the take-in and take-off times. The driving cycling was analyzed on the system in stop-start sections to compare the vehicles in a certain driving dynamics. Flow characteristic prepared instantaneously for starting vehicle time (11:06), electrical drive inlet for PHEV (11:77), depended on the road rolling criteria, ICE starting to helped SHEV (59:44) and for last the maximum speed of selected driving cycles time (2:22:05). For energy balancing, the losses of battery system, ICE losses, EM losses, brake losses and wheel losses were displayed on sankey diagrams in Fig.5.

3. CONCLUSIONS

In this study, the energy flow characteristics of PHEV vs SHEV were compared with simulation methodology. AVL Cruise is used for modelled and simulated the model HEVs. Modelled PHEV and SHEV is compared each other in terms of energy flow characteristics for under same selected conditions and explained with sankey diagrams. Comparison of different HEVs under certain conditions was explained by means of fuel consumptions, emissions and energy flow characteristics. Except NO_x, SHEV has better outputs versus to PHEV for ICE conditions. In flow characteristics, inlet and outlet energy criteria showed that larger electric devices come up with larger energy losses howbeit HEV is playing a reformative role in all performance parameters towards ICE. As a result, with selected certain values for this study, SHEV is more efficient energy usage vs PHEV.

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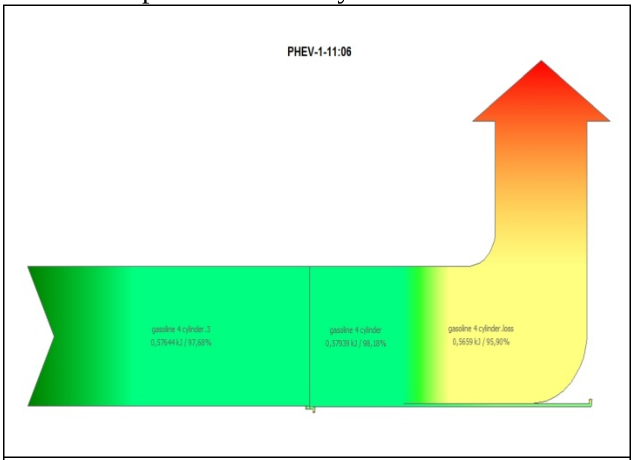

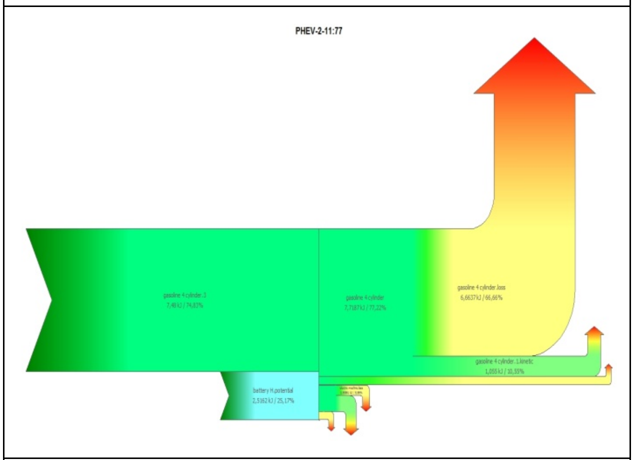

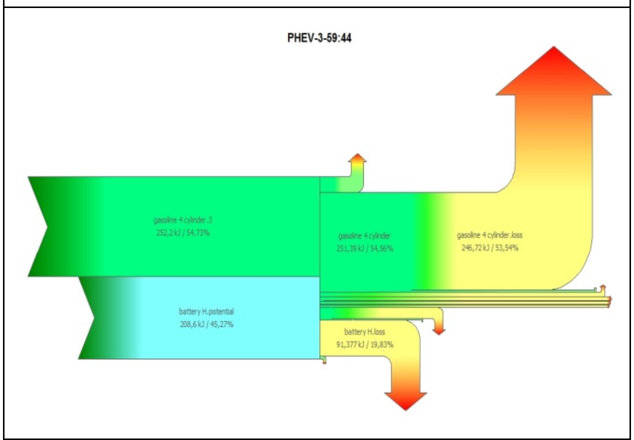

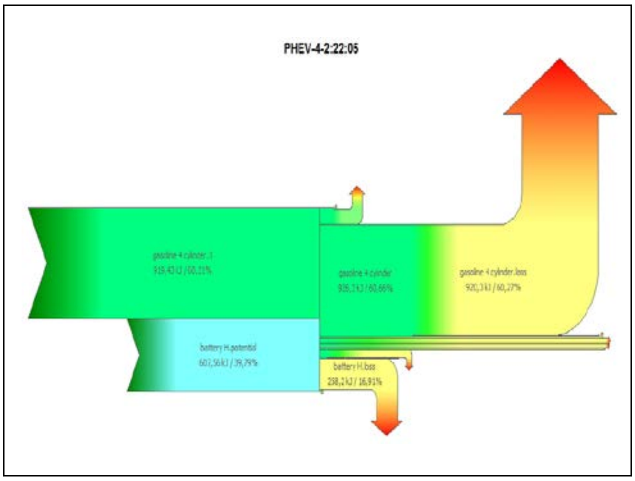

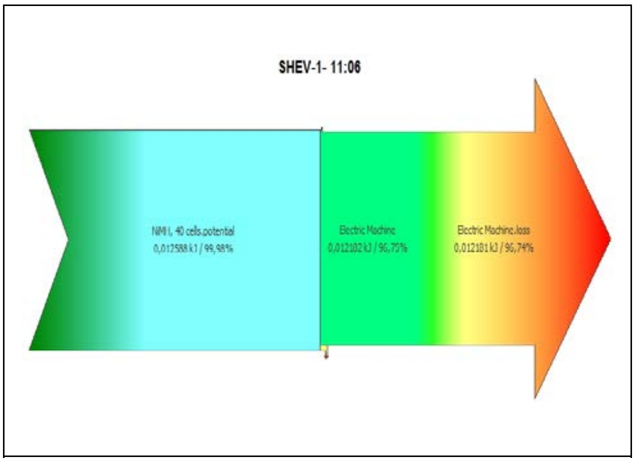

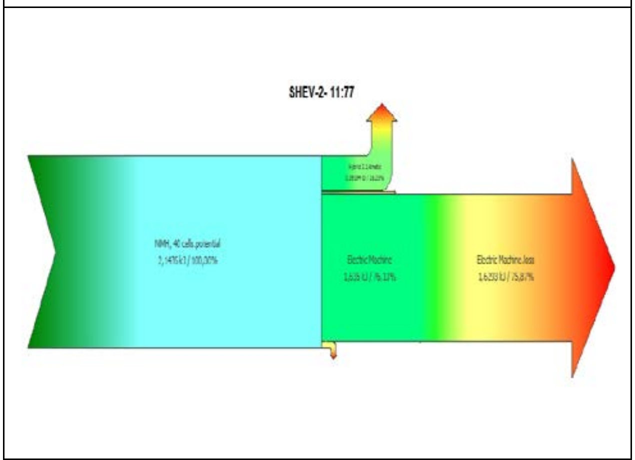

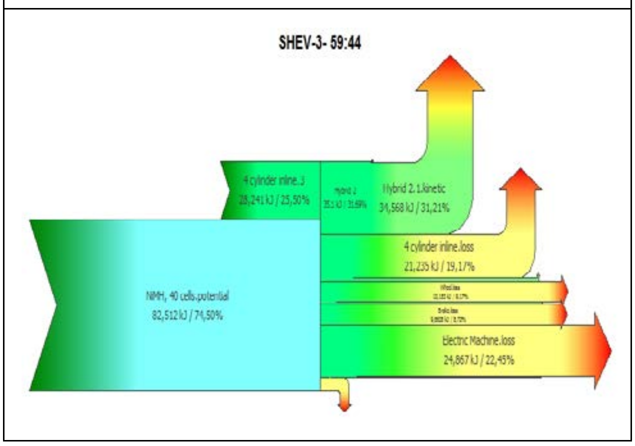

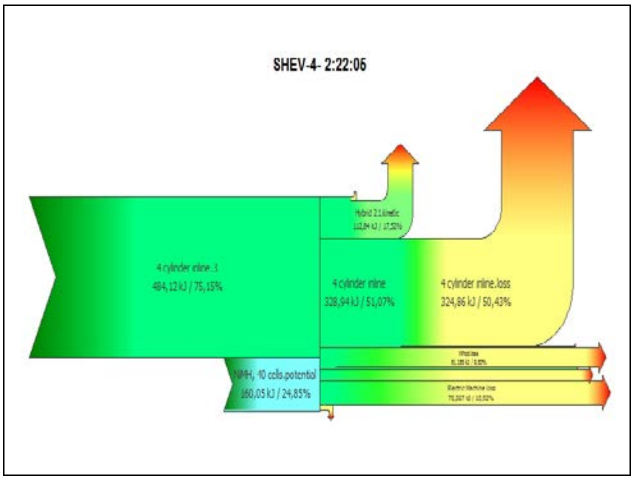

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