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An energy efficient breakdown cover service for electric cars

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Abstract

A typical breakdown cover service unit in Belgium has to assist up to 5 cars a day that end up with an empty fuel tank. As the range of today's battery electric cars is lower than what people are used to have today, breakdown cover services expect that massive introduction of electric cars will lead to a multiple of EVs ending up with an empty battery. This paper reports about a research project, initiated by a Belgian breakdown cover service, that aimed to design and build a prototype of a fast and an energy efficient intervention car for EVs with empty batteries. For the prototype a CNG van is equipped with a hybrid power system enabling efficient energy injections for electric vehicles with slow as well as fast charging possibilities. The prototype is equipped with charging infrastructure providing mode 1, 2 and 3 charging. The paper starts with a description of the prototype design. The main part gives a detailed comparison of three EV breakdown cover service methods: towing the EV, energy injection on the spot by a diesel genset on a diesel truck and energy injection with the designed prototype. For a typical breakdown cover service day, the prototype turns out to be 12% faster, consumes 41% less energy and reduces emissions by 68% in comparison with towing.

charging, infrastructure, environment, efficiency, energy source

1 Introduction

Breakdown cover services are preparing themselves for the introduction of electric vehicles. As many drivers are not yet familiar with the lower range of battery electric vehicles, it is expected that a considerable number of EV owners will end up with empty batteries. An evident solution for breakdown cover services is to pick up the car and tow it to the nearest charging point. VAB, a Belgian breakdown cover service wanted to compare this pick up method with energy injection on the spot. Therefore a prototype hybrid energy system is designed and built into a CNG van in order to provide energy injections for electric cars in a fast and energy efficient way. The prototype is called the *EVpoly*.
A picture is given on figure 1. The paper starts with the stating of the requirements for the EV breakdown cover service. The second part deals with the different components of the breakdown cover vehicle. Next, a detailed comparison between towing and energy injection on the spot with the EVpoly is given: service time, energy consumption and emissions are compared for a typical breakdown cover scenario.

Figure 1: The EVpoly: prototype of a breakdown service vehicle for EVs

2 Breakdown cover service requirements

Figure 2: Distribution of charging points in Belgium [1]

The requirements for the intended electric car breakdown cover service were well described at the start of the project. Firstly, a stranded electric car should get an energy injection for an autonomy of at least 20km. This requirement is based on today's network of charging points in Belgium as given in figure 2. Secondly, the energy injection system should suit for all EVs on the Belgian market: charging mode 1, 2 and 3 should be implemented and single phase as well as three phase charging should be possible. Thirdly, the energy injection should happen in an ecological acceptable way. A clean vehicle breakdown cover service existing of a van with an internal combustion engine and a built-in diesel genset was considered unacceptable.
Other important points for attention for the prototype design are the

- *ease of use:* the procedure for the charging of EVs with the EVpoly should be easy enough to be picked up by the operators without too much training.
- *safety:* the implementation of an energy injection system should happen with appropriate electrical protections and all live parts should be screened to limit the risk of electrocutation. Also the breakdown cover vehicle should be well ventilated.
- *robustness:* the EV poly is a road vehicle and all components should withstand normal mechanical shocks.

3 The breakdown cover vehicle

3.1 The carrier vehicle

The first idea to meet the eco specification was to integrate a hybrid genset system in an electric van. The presence of two battery packages (the van batteries and the hybrid genset batteries) should additionally have given an excellent opportunity to optimize the energy injection system for the stranded EV. Unfortunately, it turned out to be impossible yet to get an electric van delivered in the projected time scheme (april-october 2011). Therefore, a van on compressed natural gas (CNG) is chosen as the carrier for the hybrid genset. The emissions of this CNG vehicle are far below the emissions of the petrol or diesel version. Emission details for this vehicle are given in table 1. A picture is given in figure 1.

Table 1: emissions of Iveco .14 CNG F1C 6.0L EEV engine, running on G_{25} reference gas (ETC method)

	(g/kWh)
CO	1.51
non-methane hydrocarbons (NMHC)	0.019
CH_4	0.193
NO_x	0.28
hydrocarbons (HC)	0.199
CO_2	717.37
particulate matter (PM)	0.004743

3.2 The hybrid energy system

The most common way to supply energy on the spot with sufficient power is a diesel genset. The diversity of EVs makes it impossible to choose a one-size-fits-all genset for energy efficient injection on the spot. A genset may reach 35% efficiency at full load, but has a very poor efficiency at low load conditions (figure 3). Figure 3 shows the high potential for a reduction in fuel consumption for a genset when giving more attention to low loads. The use of a 40kVA genset to fastly charge an EV at 36kW may result in an energy efficiency above 30%. The use of the same genset for a slowly chargeable EV at 3.6kW let the energy efficiency drop below 10%.

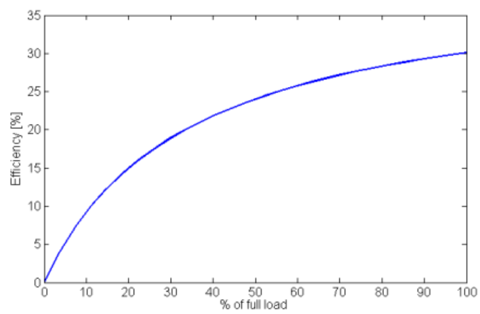

Figure 3: The efficiency of diesel genset versus load level [2]

By adding a battery pack, low loads can be delivered by that battery pack. The battery pack can be charged in advance with (green) energy supplied by the grid. The genset will only be started at higher load levels (fast charging EV) or an empty battery pack. When the nominal charger power is chosen higher than the maximum power of the genset, one is certain to charge at maximum efficiency. In earlier research projects this hybrid genset system applied for stand-alone power showed energy saving potential of over 50% [2].

The designed hybrid energy system consists of a PPO genset, a Li-ion battery pack and the appropriate battery chargers and inverters. The control of all these components is managed by a panel-PC. All components are described below and their connection is given in figure 4.

3.2.1 PPO genset

The PPO genset is a Lister Petter diesel engine that is converted to run on pure plant oil, in this case rapeseed oil. This type of fuel was chosen to accentuate the green character of the EV poly. The main adaptation is the use of a an external fuel filter that is preheated by the cooling water of the engine. The engine is coupled to a synchronous generator. The generator has two poles, so it has to run at 3000rpm in order to maintain a constant output frequency of 50Hz. Running at 3000 rpm enables to use of a smaller genset for the same power than a more conventional 1500 rpm genset. The genset can deliver 20kVA/16kW at 3x400V, 50Hz.

3.2.2 Li-ion battery pack

The Li-ion battery pack consists of 16 cells of LiFePO4 400Ah batteries, connected in series. In this way about 17kWh is available for the EV energy injections. The monitoring of the battery-pack is done by a battery management system consisting of a general control unit connected to 16 monitor- and balancing units. These units are able to balance the charge current between the batteries, up to 5 amps. The balancing is started when the cell reach a predefined voltage level. The monitor- and balancing units are mounted on an appropriate heat sink to dissipate the heat when balancing. Figure 4 shows that the battery pack may be charged by the electrical grid as well as by the genset.

3.2.3 Battery chargers, inverters

Three single battery chargers/inverters are used enabling single phase as well as three phase connections. The units were originally designed to charge lead-acid batteries, but with a manufacturer delivered software adaptation, it was possible to use them for the Li-ion battery pack. Figure 4 shows that the units are configured with two AC inputs, one connected with the synchronous machine of the PPO genset and one connected with a grid socket. These inputs can deliver 110A at 48VDC to charge the batteries and can have a power of 8000kVA to invert the DC-current to AC. There is also the possibility to boost an input with extra power from the batteries. The AC output is connected with 2 parallel sockets: one for mode 1/2 charging and one for mode 3 charging.

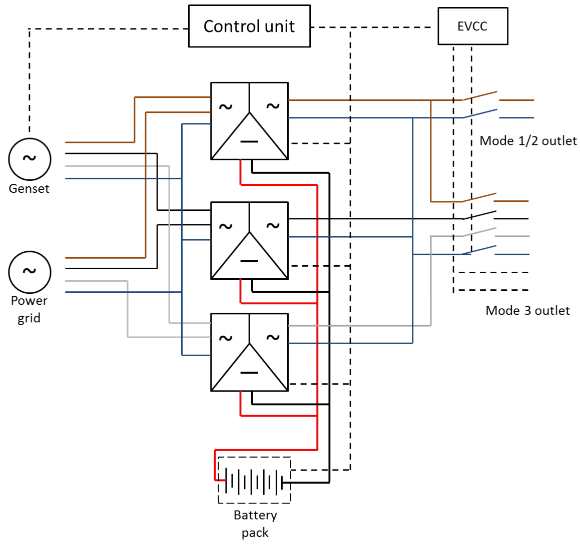

Figure 4: Electric scheme of the EVpoly hybrid power system

3.3 Charging infrastructure

The breakdown cover vehicle is equipped with charge infrastructure for different charge modes. It is able to charge mode1 and mode2 up to 230V/16A, and mode3 up to $3times$400V/52A. The system is programmed with an algorithm to deliver the energy in the most time- and energy efficient way. The most important operating modes are explained and displayed below.

3.3.1 Charging a vehicle mode 1/2 up to 16A/230V

To charge a vehicle in mode 1/2, the maximum current is 16A at 230V. This equals a power of 3680W. Delivering this energy from the genset is very inefficient because of the low load level (23% of P_{nom}). In starting condition (EVpoly with fully charged batteries), the energy is supplied from the battery pack. The energy flow is given in figure 5.

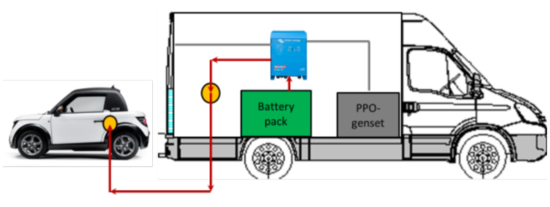

Figure 5: Charging Mode1/2 out of the batteries

When the batteries are empty, the genset will start. A part of the energy will be used to charge the vehicle, the other part will be used to charge the internal battery pack of the hybrid genset. This way, the genset is is used at full load condition, where it reaches its maximum efficiency. A scheme of the energy flow is given in figure 6.

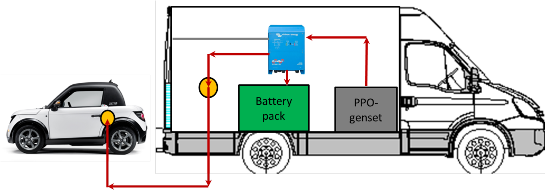

Figure 6: Recharging internal batteries while charging EV at Mode1/2

3.3.2 Charging a vehicle mode 3 up to 51A/ 3x 400V

The charging mode does not tell at what power rate the vehicle will be charged. When a mode3 plug is detected, the algorithm will determine at what power rate the vehicle will load. If the power gets below 21kW (3-phase) or 7kW (1-phase) all the energy is supplied from the battery pack (figure 6.). If the power is higher the genset will start and the energy will be supplied from the genset and will possibly be boosted by the battery pack. The genset will operate again at full load condition and thus maximum efficiency. The energy flow is displayed in figure 7.

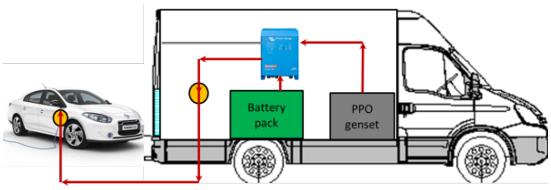

Figure 7: Charging Mod3 out of the genset and batteries

3.4 Control Unit

A panel PC is used as control unit and interacts with the operator. The control unit is given in figure 4. It controls the starts/stops of the genset as well as the power output to EV and the charging process of the lithium battery pack. For each intervention the panel PC suggests how the connected vehicle can be charged as fast and energy efficient as possible. The depth of discharge of the lithium battery pack as well as an estimate of the number of expected interventions are considered for this suggestion.

4 Breakdown cover scenario

In this paragraph different solutions for EV breakdown cover service are compared using a typical breakdown cover day scenario. During this reference day, the call center receives six consecutive calls from stranded EV-drivers. The electric vehicles have different charging capacities. The scenario assumes two slow chargers (3.7kW), two semi-fast chargers (22kW) and two fast chargers (38kW). All six vehicles are (arbitrarily) located 20km away from a charging station and 20km separated of each other (figure 8). As mentioned earlier, 20km is based on today's network of charging stations in Belgium as given in figure 2.

For this scenario three possible solutions are considered:

1. towing the vehicle to the nearest charging station with a diesel powered towing truck
2. energy injection on the spot with a diesel genset mounted on a diesel powered truck
3. energy injection on the spot with the EVpoly prototype

The three solutions are compared for the defined scenario on following points:

- total service time
- total energy consumption
- total emissions of CO_2, NO_x and particulate matter (vehicle exhaust and production of electrical energy, if applicable)

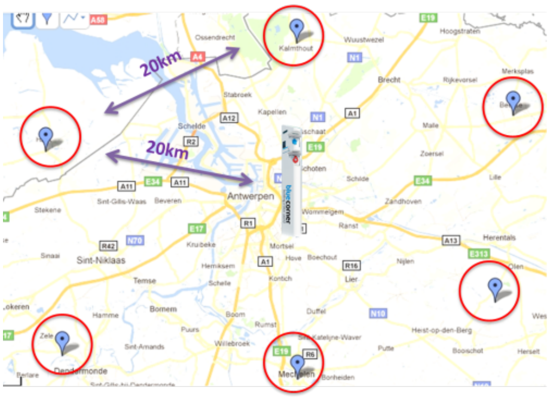

Figure 8: Localization of the six EVs in the reference scenario

4.1 Option 1: towing with diesel powered towing truck

When an EV gets stranded, the driver will call the breakdown cover service, who has to go to the stranded EV, pick it up and bring it to the nearest charging station. Years of experience by the breakdown cover service estimates that loading and unloading the vehicle takes takes about 10 minutes each. 40km, the distance back and forth, will be covered at an average speed of 70km/h. The total time needed per vehicle then equals 54 minutes. There is no difference between slow, semi-fast and fast chargers.

Years of experience of the breakdown cover service VAB lead to detailed data of the fuel consumption of their towing trucks. The average fuel consumption is 15.8*l*/100km. To tow one of the EVs, 6.32 liter diesel will be used. Based on EU emission standards and covered distance emissions can be calculated. The average emission values between Euro 4 and Euro 5 [10] are used in the calculations to reflect the mix of older and new towing trucks in the VAB fleet. In this towing option, no difference can be noticed between the different charging EV types. An overview of the total duration, fuel consumption, and emissions for this option is given in table 2.

Table 2: overview option 1

	quantity
duration	5h25min
fuel consumption	37.9*l*
emissions CO_2	102kg
emissions NO_x	80.4g
emissions PM	7.8g

4.2 Option 2: energy injection with diesel genset mounted on diesel truck

Considering the breakdown cover vehicle now has means of producing electrical energy on his own, the stranded EV battery pack can receive a partial charge on the spot. Compared with option 1 the breakdown cover vehicle doesn't have to drive back and forth, but can now drive directly from one intervention to another. This distance will always be shorter than driving back and forth to a charging station. In the proposed scenario the breakdown cover vehicle will only have to drive 20km to the next intervention.
The EV with empty battery will be charged with 4.25kWh, which should be more than enough to cover the 20km to the next charging station (or its destination). For a slow charger (3.7kW) this means that it has to charge 1h9min, a semi-fast charger (22kW) during 10min and a fast charger (maximum 38kW) during 7min. Connecting and disconnecting an EV should not take longer than two minutes in total.
The fuel consumption can be split up in two parts. An amount of diesel is used by the truck's engine (15.2*l*/100km, based on VAB's data for a small truck). This results in a fuel consumption of 3.04*l* diesel for driving. The mounted genset consumes diesel as well for the generation of electrical energy to charge the aided EVs. The fuel consumption of the genset in function of electrical load can be approximated by the empirical formula of Skarstein and Uhlen [6].

$$\text{fuel use}[l/h] = 0.246P[kW] + 0.08415P_{\text{rated}}[kW] \quad (1)$$

The fuel consumption is 4.90*l* diesel for a slow charger, 1.66*l* for a semi-fast charger and 1.40*l* for a fast charger.

The driving emissions are calculated as in option 1 (paragraph 4.1). The genset emissions are based on the European Stage III B Standards for Nonroad Engines [11]. An overview of the total duration, fuel consumption and emissions are given in table 3.

Table 3: overview option 2

quantity	driving	genset	**total**
duration	1h43min	3h04min	**4h47min**
fc diesel	18.2*l*	15.9*l*	**34.2*l***
emissions CO_2	48.9kg	42.7kg	**91.5kg**
emissions NO_x	40.2g	84.1g	**124g**
emissions PM	3.90g	0.638g	**4.54g**

4.3 Option 3: energy injection on the spot with the EVpoly

When an EV ends up with an empty battery, the vehicle will be helped by charging the batteries on the spot, as in option 2. But the breakdown cover service vehicle consists now of a CNG van, with a built in hybrid power source.
The duration of the interventions is the same as in option 2: driving distance and charge times are identical.
The fuel consumption is now split up in three parts: driving, delivering energy from the EVpoly battery pack and delivering energy from the PPO genset all consume energy. CNG is used as fuel for the breakdown cover vehicle. Driving tests with the vehicle have shown that the fuel consumption is about 13m^3/100km CNG. The "fuel consumption" for the energy supply depends on the type of EV being charged. When a slow charging vehicle is charged, all the energy will be delivered by the batteries. There is assumed that those batteries were charged in advance with energy from the grid. Using an efficiency of 90% for charging the internal batteries and 90% for discharging the internal batteries (maximum efficiency of the inverters use is 96% [7]), 5.25kWh was drawn from the grid to charge one vehicle out of the batteries. Charging an semi-fast charging vehicle is hardly different from the slow charging vehicle concerning the "fuel consumption". The increase of losses at higher currents is compensated by a better efficiency of the inverters. So, the energy will also be supplied by the battery pack.
For a fast charging EV, one part (2.46kWh) of

Table 4: total emissions for option 3

	driving	PPO-genset	Batteries
CO_2	26.9kg	3.70kg	11.6kg
NO_x	15g	13.2g	8.7g
PM	0.545g	0.059g	0.0479g

the energy will be supplied by the batteries and another part (1.79kWh) will have to be supplied by the PPO genset. Considering the charge and discharge efficiencies of the internal batteries, 3kWh will be supplied by the grid for each fast charging EV. To determine the fuel consumption of the PPO-genset, a empirically obtained PPO version of the formula of Skarstein and Uhlen[6] is used. The fuel consumption would be $0.67l$ for one fast charging EV. Emissions per part are given in table 4. An overview of the total duration, fuel consumption and emissions for option 3 are given in table 5 [5][10][4][8][9].

Table 5: overview option 3

	quantity
duration	4h47min
fc CNG	15.6m^3
fc PPO	1.34l
fc electrical energy	29kWh
emissions CO_2	42.2kg
emissions NO_x	36.9g
emissions PM	0.647g

4.4 General comparison

Table 6 gives an overview of duration, energy consumption and emissions for the breakdown cover scenario for the 3 options. The time gain seems to be rather limited. The energy injection options are 12% faster than towing the EV. The main reason is the limited charging speed of many of today's EVs. An energy injection for 20km for a slow charger takes at least one hour. The introduction of more semi-fast and fast EVs will increase the time gain.
Concerning the primary energy use and emissions, the EVpoly option is by far the most efficient option. The primary energy use of the option with the EVpoly is 41% less than the towing option. The emission of CO_2 is reduced by 58%, NO_x-emission is reduced by 54% and PM emissions are reduced by 92%.

5 Future research

Today the EVpoly is only used for training sessions for employees of VAB. In the near future charging tests will be performed and breakdown cover scenario's will be executed with different EVs with different charging capabilities. These tests will lead to optimization of the prototype. Depending on the evolution of the EV market the possibility of the implementation of mode 4 DC charging will be considered.

6 Conclusion

The described EVpoly project shows that energy injection on the spot for EVs with empty batteries can compete with the speed of towing the EV to the nearest charging point when limiting the energy injection for an autonomy of 20km. With more fast chargers than slow chargers on the road, the EVpoly is even faster than towing. Moreover by using well-sized hybrid energy systems for the energy injection, the poor energy efficiency of gensets at low load levels can be compensated. The possibility of charging the battery pack of the hybrid system with green energy from the grid also favors the energy efficiency. The EVpoly prototype used for a typical breakdown cover scenario leads to serious reductions of primary energy use and emissions.

Table 6: general comparison

	option 1	option 2	option 3
duration	5h25m	4h47m	4h47m
primary energy use	37.9l diesel	34.2l diesel	15.6m^3 CNG
			1.34l PPO
			29kWh electrical energy
total primary energy	406kWh	366kWh	238kWh
CO_2	102kg	77.4kg	42.2kg
NO_x	80.4g	124g	36.9g
PM	7.8g	4.5g	0.647g

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