Electrification of off-road vehicles: examining the feasibility for the Italian market

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Abstract

The study, made by ENEA in cooperation with the University of Pisa as part of the activities supported by the Italian Ministry of Economic Development in the framework of the Program Agreement for the Research on the Electric System, is related to the situation of Italian market and demonstrates the feasibility of the electrification for off-road vehicles and the possibility to realize it by the means of standard modules. The preliminary dimensioning of the standard modules is also reported, defining the main electric characteristics (voltage and capacity) and the type of chemistry: LiFePO₄ is proved to be a very effective solution for this kind of application. The activity goes on towards the final design and the realization of demonstrator units.

Keywords: electrification, off-road vehicles, lithium battery, battery module, LiFePO₄

1 Introduction

There are a lot of medium/little companies, working in the fields of the machines for building sites, gardening, streets cleaning, earth-moving, agricultural greenhouses, that use for their production diesel and gasoline engines. The comparison between the actual diesel and electric motorizations for industrial vehicles and working machines, shows the advantage of the electric motorization as for the global energetic consumptions (from the source to the user) as for the environmental impact (reduction of CO₂ emissions).

The electrification of “off-road” fields, could bring a large market, equivalent to the introduction on the market of tens of thousands electric cars in a year.

For these reasons, a special technical-scientific study was made by ENEA in cooperation with the University of Pisa to value the potential market of off-road vehicles in electric version [1].

2 The potential market of off-road electric vehicles at 2020 in Italy

2.1 General aspects

As a first step, a lot of different types of electric machines already on the market were individuated, a part of them is shown in Annex 1.
Then, the sectors of potential interest for the study were chosen: machines form building sites, gardening, machines for the street cleaning, agricultural machines, machines for earth-moving, machines for agricultural greenhouses, snow machines. The study was related to motorizations, typically medium/low power, where it’s possible the substitution of the actual supply systems with innovative battery systems. High power motorizations or duty cycles which require hybrid propulsion or too much expensive applications (due to the big number of batteries) were excluded.

2.2 Potentiality

By the data of sales of off-road vehicles in Italy in 2009 and 2010 (Figure 1 and Figure 2), on kind courtesy of manufacturers’ associations or the companies working in this field, it was calculated the potential sales volume of off-road vehicles at 2020 in the different sectors, and finally the potential of off-road electric vehicles at 2020, with the hypothesis that the production of electric vehicles is only 10% of the total.

Considering the type and number of lithium batteries for each type of vehicle, this potential sales volume was converted in kWh, as shown in Figure 3.

![Figure 3: Potential sales volume of off-road vehicles at 2020 for different sectors](image)

At the unitary cost of 400 €/kWh, expected target for traction batteries, these volumes correspond to over 200 M€ of sales. As number of electric cars, with the hypothesis that 25 kWh is the energetic content of the battery system for a medium car, the above off-road market at 2020 corresponds to rather 20,000 electric cars. Considering that at 2020 is estimated a penetration of the pure electric equal to 3÷4% on a global car market of 1.6 ÷ 2.6 million cars, the above-mentioned parallel market corresponds to the 25÷30% of the electric car market.

2.3 Main characteristics of the battery pack

In the framework of the selected categories, it was realized a list of 64 vehicles (see Annex 2) and for each one of them the main characteristics (kWh and kW) of the battery pack were preliminary determined (see Annex 3).

The result of the study is shown in Figure 4: two capacity levels, 120 Ah and 180 Ah, and three voltage levels, 48 V, 96 V, and 192 V, are able to satisfy all what is needed for the electrification of this type of vehicles.
3 The feasibility of a standardization

During the various contacts with the manufacturers it was found that the main problems which obstruct the large diffusion of the electric vehicles are the big initial cost due to the big cost of batteries and the short autonomy. A valid argument to reduce prices is the adoption of standard modules: in fact, an hypothetical economic operator could satisfy the needs of the various applications with the same product and this can be translated in high volumes of production/purchasing. The modularity, associated with the use of small-sized modules and charge stations, could permit to reduce the weight of the battery pack, that is another constrictive factor because of its impact on the kilometric consumptions.

4 Standard modules

To define the standard modules means to establish the type of technology and the main electric characteristics: voltage and capacity.

4.1 Technology and main electric characteristics of the standard modules

About the type of technology, the LiFePO$_4$ was chosen as cathode material because of safety and costs, even if the specific values of power and energy of this technology are lower than some other technologies. On the other hand, the off-road vehicles have less constrictive conditions about space and weight than the road vehicles and anyway the comparison between a lithium iron phosphate battery and the equivalent lead-acid battery shows that the volume and weight can be reduced. Figure 5 shows the comparison between the dimensions of a lithium-ion battery LiFePO$_4$ 12V – 100Ah (weight 15.8kg) and a lead acid battery 12V – 100Ah (weight 42.2kg): in this case, the volume is reduced by half and the weight by about 60%.

Further the LiFePO$_4$ technology was proved as the best technology for the application of lithium batteries as starting lighting ignition batteries due to its characteristic working voltage: in fact, the series connection of 4 LiFePO$_4$ cells equals the working voltages of the electric suppliers and the lead acid starting batteries actually on board the vehicles [2]. The use of the same technology for different applications is a factor of standardization and reduction of costs.

![Figure 5 – Comparison between the dimensions of a lithium iron phosphate battery (left) and an equivalent lead acid battery (right)](image)

Figure 6: Energy released at various temperatures for the different cathode materials

Figure 6 is relating to the rupture of cathodes of various technologies by the effects of temperature and it shows that the LiFePO$_4$ cathode breaks at higher temperatures than other technologies and also the energy released is lower.

A particular study was conducted also about the costs of LiFePO$_4$ technology, to clarify contrasting information coming from the literature: the study considered the history of purchases at ENEA, followed by an analysis of costs of 54 models of batteries with different chemistries and suppliers, and a valuation of the costs per kW for different type of chemistries.

| Level     | Chemistry | Characteristics | € per kWh | Date   | Note |
|-----------|-----------|-----------------|-----------|--------|------|
| module    | NMC       | 86V 40Ah        | 699       | June 2010 |      |
| system    | NMC       | 48V 20Ah        | 1656      | June 2010 | BMS  |
| module    | LFP       | 12V 100Ah       | 889       | June 2010 | BMS  |
| module    | NMC       | 86V 40Ah        | 600       | Jan 2011  | BMS  |
| cell      | LFP       | 3.2V 30/60/100Ah| 276       | May 2011  |      |

Table 1: History of recent purchases of lithium ion batteries at ENEA
In the history of recent purchases of lithium ion batteries, shown in Table 1, the chemistry LFP (LiFePO$_4$) was the type of technology which corresponded the lowest cost.

Table 2: Cost comparison of lithium ion batteries of various technologies and suppliers

| Characteristics | Cost | Unit Cost | Chemistry | Supplier |
|-----------------|------|-----------|-----------|----------|
| V               | AH   | €/kWh     | LCO       | K        |
| 3.7             | 1.8  | 3.18      | 477.477   | LFP      |
| 3.2             | 0.6  | 7.74      | 4031.25   | K        |
| 3.7             | 1.95 | 10.32     | 1430.35   | ?        |
| 3.2             | 1.4  | 4.76      | 1062.5    | LFP      |
| 3.2             | 1.25 | 6.34      | 1585      | LFP      |
| 3.7             | 2    | 6.15      | 831.081   | LCO      |
| 3.3             | 2.3  | 14.55     | 1916.99   | LFP      |
| 3.2             | 3    | 7.93      | 826.047   | LFP      |
| 3.2             | 3.2  | 9.13      | 891.601   | LFP      |
| 3.2             | 2.5  | 10.32     | 1290      | LFP      |
| 3.6             | 50   | 129.26    | 718.111   | LCO      |
| 3.2             | 40   | 53.99     | 421.796   | LFP      |
| 12.8            | 16   | 197.68    | 965.234   | LFP      |
| 3.2             | 50   | 98.44     | 615.25    | LFP      |
| 12              | 10   | 198.48    | 1654      | LFP      |
| 3.6             | 90   | 232.66    | 718.086   | LFP      |
| 3.2             | 60   | 80.98     | 421.770   | LFP      |
| 3.74            | 100  | 528.74    | 1413.74   | LFP      |
| 3.6             | 100  | 258.52    | 718.111   | LCO      |
| 3.2             | 90   | 121.47    | 421.770   | LFP      |
| 3.2             | 100  | 178.63    | 558.218   | LFP      |
| 12              | 20   | 373.13    | 1554.70   | LFP      |
| 24              | 10   | 396.95    | 1653.95   | LFP      |
| 3.6             | 200  | 517.03    | 718.097   | LFP      |
| 3.2             | 160  | 215.94    | 421.757   | LFP      |
| 12              | 30   | 547.79    | 1521.63   | LFP      |
| 36              | 10   | 595.43    | 1653.97   | LFP      |
| 3.2             | 200  | 317.56    | 496.187   | LFP      |
| 12.8            | 42   | 682.76    | 1270.01   | LFP      |
| 3.2             | 200  | 364.4     | 569.375   | LFP      |
| 12              | 40   | 722.45    | 1505.10   | LFP      |
| 24              | 20   | 746.27    | 1554.72   | LFP      |
| 48              | 10   | 793.9     | 1653.95   | LFP      |
| 12              | 60   | 1095.9    | 1521.65   | LFP      |
| 24              | 30   | 1095.5    | 1521.65   | LFP      |

In Table 2, where a comparison between the cost of lithium ion batteries of various technologies (LiFePO$_4$, LFP, nickel-cobalt-oxide, NCO and nickel-cobalt-manganese, NMC) and suppliers is shown, the prices are relating to the year 2010, but the comparison is useful in any case. The consent of the various suppliers to publish the data was not asked for, so each supplier is simply indicated by a letter. The analysis of the values in the table gives the following average costs:

- average cost LCO 751.1583 €/kWh
- average cost LFP 1300.484 €/kWh
- average cost NMC 1422.048 €/kWh

Some of the values in Table 2 are referred to battery module or complete battery systems, i.e. the systems with tension equal or above to 12,8V, where the cost of the electronics is enclosed. With reference to the average cost calculated considering all the suppliers, the LFP technology is situated in the middle.

The supplier indicated by the letter T manufactures different types of chemistry and its cost are surely referred only to the cell: if the average costs are calculated considering only the supplier T, the analysis gives the following results:

- average cost LCO 807.8657 €/kWh
- average cost LFP 471.3871 €/kWh

This kind of analysis seems to be better because the comparison is really made in the same way.
conditions: in this context the technology LFP is the cheapest.

If the lowest cost in all the table is found, it belongs to an LFP battery (421€/kWh).

A final consideration can be made about the costs of various technologies as a function of power. Also from this analysis, shown in Table 3, the LFP technology turns out advantageous. Further, the LFP technology is on development yet, so it could be susceptible of other cost reductions.

Table 3: Cost per kW estimation for various types of chemistry

| Chemistry | Cost [€/kW] |
|-----------|-------------|
| NCA       | 40          |
| LMO/LTO   | 40          |
| LMO/C     | 40          |
| LFP       | 30          |

Following these considerations the LiFePO₄ technology was proved to be a very effective solution for the application of electric off-road vehicles.

From the data of the battery packs preliminary determined (Annex 3 and Figure 4), it can be seen that adopting 12 V as standard module voltage and three values of capacity, 30Ah, 60Ah, and 90÷100Ah, it is possible realize standard modules (module 12V - 30Ah, little size, module 12V - 60Ah, medium size, and module 12V - 90÷100 Ah, large size) which can be used, taken individually or series/parallel connected, to satisfy all the applications above-mentioned. The standard modules can be realized by 4 cells LiFePO₄. On the other hand, 12 V is the standard voltage for starting batteries and the above capacities were selected in the previous study [2] for the application starting ignition batteries: these are other factors of standardization.

4.2 Preliminary specifications of the standard modules

This specification contains all the main information to realize the preliminary design and further the prototype of the battery module. Following some tests on the prototype, it will be issued a final specification for the definitive module.

4.2.1 Standards

As the prototypes as the final modules will be realized according to the main International standards relating to the safety and functionality when an electric storage system is used on an electric vehicle. The following Table 4 shows the main standards considered in the modules design.

Table 4: Main standards relating to the safety when an electric storage system is used on the vehicles

| Name       | Title                                                                 |
|------------|-----------------------------------------------------------------------|
| ISO 6469-1 | Safety specifications – Part 1: On-board electrical energy storage    |
| ISO 6469-2 | Safety specifications – Part 2: Vehicle functional safety             |
| ISO 6469-3 | Safety specifications – Part 3: Protection of persons against electric hazards |

4.2.2 Main components of the modules

The module must enclose:

- the single cells and their connections,
- the Battery Management System (BMS) at module level, type “built-in”, made by an electronic system for monitoring the state of charge (SOC), current, total voltage, single cells voltage and temperature, a protection system, a balancing system and a data communication system,
- a thermal system, built in the module,
- a power interface, with power connectors IP57, isolation detecting and additional equipments (fast fuses on both the poles),
- enclosure, with supports and other equipments for handling (lifting cords) and installation, powder and water resistant IP56, flame retardant material.

The following Figure 7 shows a simple drawing of the module, with its main components and communication interfaces.

Figure 7: Preliminary scheme of the battery module with BMS

4.2.3 Power

- peak power during discharge (10s): about 2 kW (little size), 4 kW (medium size), 7 kW (large size) , at 25°C, until SOC 20%,
medium power during charge and discharge: about 0.5 kW (little size), 0.75 kW (medium size), 1.5 kW (large size).

4.2.4 Voltage
- minimum voltage during discharge: 10.0 V.
- maximum voltage during charge: 15.4 V.

4.2.5 Self discharge
the allowed self discharge in one month will be less than or equal to 3% of nominal capacity.

4.2.6 Enclosure
The module must be realized in a unique enclosure and its installation on board the vehicle must come without requiring important mechanical modifications. As a reference for the dimensions of the module was taken the actual configuration of the lead acid batteries, so the maximum overall dimensions should possibly be as following:
- length: ≤ 260 mm,
- width: ≤ 173 mm,
- height: ≤ 225 mm,
- weight: ≤ 16 kg (large size).

4.2.7 Thermal management
The prototype will be initially realized without a thermal system. The experimental activity on it will show if a cooling system is needed and, if a cooling system is needed, which is the type of it (forced air or liquid).
To verify if a thermal system is needed, and to design it if necessary, it is assumed as a reference the profile reported in CEI EN 61982-3 Standard. This profile is typical of a full electric vehicle and is shown in Figure 8: it consists of some charges and discharges at different power and it must be repeated till the condition of minimum voltage is reached.
The powers indicated in Figure 8 are relating to a standard battery with energy 40 kWh at nominal power: this battery is able to supply a full electric vehicle with 2000 kg weight for 250km. To make tests on littler batteries the values of power must be reduced by a scale factor (fs) equal to the ratio between the nominal energy of the standard battery and the energy of the battery on test (for example, if the battery on test has a nominal energy 10 kWh, the reducing factor fs will be 4).

Table 5 shows the power set-up and the length of the single steps of the test.

| Step N. | Length [s] | Power [kW] |
|---------|------------|------------|
| 1       | 16         | 0          |
| 2       | 28         | 8/fs       |
| 3       | 12         | 16/fs      |
| 4       | 8          | -8/fs      |
| 5       | 16         | 0          |
| 6       | 24         | 8/fs       |
| 7       | 12         | 16/fs      |
| 8       | 8          | -8/fs      |
| 9       | 16         | 0          |
| 10      | 24         | 8/fs       |
| 11      | 12         | 16/fs      |
| 12      | 8          | -8/fs      |
| 13      | 16         | 0          |
| 14      | 36         | 8/fs       |
| 15      | 8          | 64/fs      |
| 16      | 24         | 39,2/fs    |
| 17      | 8          | -16/fs     |
| 18      | 32         | 16/fs      |
| 19      | 8          | -32/fs     |
| 20      | 44         | 0          |

4.2.8 Calendar life
It must be comparable with the life of the actual lead acid batteries (also for psychological reasons of the potential buyer), so 6 – 8 years.
Life as number of cycles corresponding to the calendar life: this definition requires to know the duty cycle typical of the off-road vehicles. Because of the lack of this information, it is temporarily assumed the ECE cycle shown in Figure 9 (duration 1200s and length 11.67 km). Considering a medium travel of 15.000km, the cycles number which corresponds to 6 – 8 years of
calendar life becomes $7.500 - 10.000$ ECE cycles. The test profile is made by some charges and discharges at different power and it must repeated till the minimum voltage is reached. At the end of this procedure the battery must be completely charged. The power set-up shown in the Figure 9 are relating to a standard battery with 15 kWh of energy at the nominal power, able to supply a full electric vehicle 1.150kg in weight for 113km. To make tests on littler batteries, the power values can be reduced by a scale factor ($f_s$), equal to the ratio between the nominal energy of the standard battery and the power of the battery on test (for example, if the nominal energy of the battery on test is 5 kWh, the value of $f_s$ will be $3$).

A further verify will be conducted on the duty cycle of the off-road vehicles and the length of life as cycles number will be recalculated.

### 4.2.9 Environmental conditions
- environmental temperature: -20°C ÷ +50°C,
- working temperature: -20°C ÷ +55°C,
- humidity: 0 ÷ 100%.

### 4.3 Preliminary design of the standard modules

The little size module can be realized by the cell type HP-PW-30Ah (manufacturer Shangdong Hipower New Energy Group Co. Ltd), whose main characteristics are shown in Table 8.

#### Table 6: Urban ECE Cycle

| Step N. | Length [s] | Power [W] |
|---------|------------|-----------|
| 1       | 11         | 0         |
| 2       | 4          | 4250/fs   |
| 3       | 8          | 750/fs    |
| 4       | 5          | -1075/fs  |
| 5       | 21         | 0         |
| 6       | 12         | 6975/fs   |
| 7       | 24         | 1950/fs   |
| 8       | 11         | -2150/fs  |
| 9       | 21         | 0         |
| 10      | 26         | 8875/fs   |
| 11      | 12         | 4000/fs   |
| 12      | 8          | -3250/fs  |
| 13      | 13         | 2225/fs   |
| 14      | 12         | -2350/fs  |
| 15      | 7          | 0         |

#### Table 7: Extra-urban ECE Cycle

| Step N. | Length [s] | Power [W] |
|---------|------------|-----------|
| 1       | 20         | 0         |
| 2       | 41         | 12575/fs  |
| 3       | 50         | 7725/fs   |
| 4       | 8          | -6125/fs  |
| 5       | 69         | 4000/fs   |
| 6       | 13         | 18350/fs  |
| 7       | 50         | 7725/fs   |
| 8       | 24         | 19875/fs  |
| 9       | 83         | 13575/fs  |
| 10      | 22         | -7650/fs  |
| 11      | 20         | 0         |

#### Table 8: Main characteristics of the cell for the little size standard module

| Specific | Value |
|----------|-------|
| Voltage [V] | 3.20 |
| Nominal capacity [Ah] | 30 |
| Dimensions, terminals enclosed (L*W*H) [mm] | 103x41x168 |
| Weight [kg] | 1.15 |
| Discharge @ +23 °C | Max. cont. current [A] 90 |
| | Peak @ 60 sec [A] 150 |
| | Cut - off [V] 2.50 |
| Charge @ +23 °C | Charge Method CC/CV (3.65 V) |
| | Max. cont. current [A] 30 |
| | Cut – off [V] 3.85 |
The module will be made by 4 cells series connected. So the main characteristics of the module become as shown in Table 9.

Table 9: Main electric characteristics of the little size standard module for electric off-road vehicles

|                  | Value   |
|------------------|---------|
| Nominal voltage [V] | 12.80   |
| Nominal capacity [Ah] | 30      |
| Minimum weight [kg]  | 4.6     |
| Maximum specific energy [Wh/kg] | 83      |
| Maximum energy density [Wh/l] | 135     |
| Discharge @ +23 °C  |
| Max. cont. current [A] | 90      |
| Peak @ 60 sec [A]     | 150     |
| Cut - off [V]         | 10      |
| Charge @ +23 °C       |
| Charge method CC/CV   | (14.6 V)|
| Max. cont. current [A] | 30      |
| Cut – off [V]         | 15.4 V  |

The medium size module can be realized by the cell HP-PW-60Ah (manufacturer Shangdong Hipower New Energy Group Co. Ltd), whose main characteristics are shown in Table 10.

Table 10: Main characteristics of the cell for the medium size standard module

|                      | Value  |
|----------------------|--------|
| Nominal voltage [V]  | 12.80  |
| Nominal capacity [Ah] | 60     |
| Dimensions, terminals enclosed (L*W*H) [mm] | 114x61x203 |
| Weight [kg]          | 3.40   |
| Discharge @ +23 °C   |
| Max. cont. current [A] | 180    |
| Peak @ 60 sec [A]    | 300    |
| Cut - off [V]        | 2.50   |
| Charge @ +23 °C      |
| Charge method CC/CV  | (3.65 V)|
| Max. current cont. [A] | 100   |
| Cut – off [V]        | 3.85   |

The large size module can be realized by the cell HP-PW-100Ah (manufacturer Shangdong Hipower New Energy Group Co. Ltd), whose main characteristics are shown in Table 12.

Table 12: Main characteristics of the cell for the large size standard module

|                  | Value   |
|------------------|---------|
| Nominal voltage [V] | 12.80  |
| Nominal capacity [Ah] | 100    |
| Dimensions, terminals enclosed (L*W*H) [mm] | 163x51x278 |
| Weight [kg]       | 4.40   |
| Discharge @ +23 °C |
| Max. cont. current [A] | 300    |
| Peak @ 60 sec [A] | 500    |
| Cut - off [V]     | 2.50   |
| Charge @ +23 °C   |
| Charge method CC/CV | (3.65 V)|
| Max. current cont. [A] | 100   |
| Cut – off [V]     | 3.85   |

The module will be made by 4 cells series connected. So the main characteristics of the module become as shown in Table 13.

Table 13: Main electric characteristics of the large size standard module for electric off-road vehicles

|                  | Value   |
|------------------|---------|
| Nominal voltage [V] | 12.80  |
| Nominal capacity [Ah] | 100    |
| Minimum weight [kg]  | 13.60  |
| Maximum specific energy [Wh/kg] | 94      |
| Maximum energy density [Wh/l] | 138     |
| Discharge @ +23 °C  |
| Max. cont. current [A] | 300    |
| Peak @ 60 sec [A]    | 500    |
| Cut - off [V]        | 10     |
4.4 Demonstrator

As an example of the modules design, it was decided to realize a modular storage system. It was chosen the working condition 48V – 200Ah, corresponding to \(9 \div 10\ kWh\), that is good for a lot of machines in the field of “off-road vehicles for gardening”, for example PK600 (manufacturer Grillo SPA), Tigercar and Tigercar+ (manufacturer Antonio Carraro SPA), ATX 200E (manufacturer Alké). Figure 10 gives an image and Table 14 shows the main characteristics of the ATX 200E.

| Charge @ +23 °C | Charge method | CC/CV (14.6 V) |
|----------------|---------------|----------------|
|                | Max. cont. current [A] | 100            |
|                | Cut – off [V]     | 3.85           |

Table 14 – Main characteristics of the off-road vehicle ATX 200E

![Figure 10 – Off-road vehicle ATX 200E](image)

The supply system for this vehicles could be made by 2 groups of lithium-ion battery systems, each one 48V – 100Ah (the two systems together give 48V – 200Ah reported in the above text and in Table 14). Each group can be realized by 4 large size standard modules, series connected. The demonstrator system was realized firstly in a prototype version. It will be followed by the final version: in this version, each module will have its BMS “built-in”, to whom the BMS at system level (BMS master) will be added.

![Figure 11 – Prototype version of the demonstrator](image)

Table 15: Main electric characteristics of the modular storage system 48 V for each drive train of an off-road gardening vehicle

| Specific                                      | Value          |
|----------------------------------------------|----------------|
| Nominal voltage [V]                          | 51.20          |
| Nominal capacity [Ah]                        | 100            |
| Minimal dimensions (L*W*H) [mm]              | 652 x 204 x 278 |
|                                              | 326 x 408 x 278 |
| Minimum weight¹ [kg]                         | 54.4           |
| Max. specific energy [Wh/kg]                 | 94             |
| Max. energy density [Wh/l]                   | 138            |

| Discharge @ +23 °C                          | Value          |
|---------------------------------------------|----------------|
| Max. cont. current [A]                      | 300            |
| Peak @ 60 sec [A]                           | 500            |
| Cut - off [V]                               | 40             |

| Charge @ +23 °C                             | Value          |
|---------------------------------------------|----------------|
| Charge method CC/CV (58.4V)                 |                |
| Max. cont. Current [A]                      | 100            |
| Cut – off [V]                               | 61.60          |

Table 15 shows the main electric characteristics of the storage system for the vehicle taken as an example. In Annex 4 some tables relating to the specifics of the BMS are reported.

5 Conclusions

The study, made by ENEA in cooperation with the University of Pisa as part of the activities supported by the Italian Ministry of Economic Development in the framework of the Program Agreement for the Research on the Electric
System, demonstrated the feasibility of the electrification for off-road vehicles and the possibility to realize it by the means of standard modules. The preliminary dimensioning of the standard module was made and the activity goes on through the study of the thermal management and the final specifics of the BMS, especially regarding the balancing function (how to balance, in active or passive way, and when) of the module. The thermal management and the BMS will be enclosed in the box of the module in the definitive version. A BMS master will be also developed to realize the management of a battery system made by modules series/parallel connected.

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Massimo Ceraolo was born in 1960. He received his Master’s degree (with honours) in electrical engineering from the University of Pisa, Italy in 1985. He is currently a Full Professor of electric power systems and on-board electric systems at the University of Pisa, Italy. He also teaches naval electric systems at the Italian Naval Academy, in Livorno, Italy. His research interests include electrochemical systems and electric, hybrid electric and fuel cell vehicles.

Tarun Huria was born in 1973 in India. He received his M.S. degree in information technology from Punjab Technical University, Jalandhar, India in 2004, and since 2009 has been working towards his Ph.D. degree in land vehicles and transport systems from the University of Pisa, Italy. He worked for the Indian Railways from 1995 to 2009. His research interests include modelling and control of hybrid electric vehicles and energy storage, especially for heavy road and rail vehicles.
ANNEX 1

Some electric machines already on the market

**MINIDUMPERS**

| Model: HINOWA HS 400 | Electric motor: asynchronous |
|----------------------|-----------------------------|
| Max gross power: 2 kW at 3100 rpm |
| Width: 790 mm |
| Height: 1162 mm |
| Length: 1676 mm |
| Tank volume: 115 dm³ |
| Weight: 640 kg |
| Max capacity: 300 kg |

**AERIAL PLATFORMS**

| Model: HINOWA GOLDLIFT 14.70 | Lithium-Ion |
|-----------------------------|-------------|
| Electric motor: 2kW at 48V |
| Dimensions: 180x72x37cm |
| Weight: 1790 kg |
| Speed: 1,4 km/h |
| Max gradient: 18.5° (33.5%) |

**ROAD SWEEPERS**

| Manufacturer: U.C.M. S.r.l. (UNIECO Group) |
| Model: 360 Electric |
| Electric motor: asynchronous on each rear wheel |
| Power: 5 kW (continuous working) |
| Dimensions: 2775x980x1860mm |
| Battery: 2x48V, 650 Ah |
| Recharge time: 5-8h |

**WASTE COMPACTERS**

| Manufacturer: OMB INTERNATIONAL Srl |
| Model: CM 1900 hybrid (full electric during pick-up) |
| Recharge time: 20min, by a thermal motor and a generator |
| Dimensions: 6.5x1.8x3.2m |
| Weight: 15ton (useful charge 4.000kg) |
## ANNEX 2

### Sectors and machines of potential interest for the study

| TYPE OF MACHINE          | MODEL OR TYPE | MANUFACTURER                                      |
|--------------------------|---------------|--------------------------------------------------|
| **BUILDING SITES MACHINES** |               |                                                   |
| Chargers with telescopic arms | P 25.6        | MERLO SPA                                        |
|                          | MLT 731 TURBO | MANITOU COSTRUZIONI INDUSTRIALI SRL              |
|                          | LM1330/LM1333 | CNH ITALIA CONSTRUCTION MACHINERY SPA            |
| Mini conveyers / Mini dumpers | ROSSETTO TRV 10 | F.LLI MESSERSI SPA                             |
|                          | HS 400 (ELECTRIC) | HINOWA SPA                                         |
|                          | SERIES 50    | CORMIDI SRL                                      |
|                          | CINGO M 10.2 PLUS | MERLO SPA                                        |
| Aerial platforms         | C 12.65      | CORMIDI SRL                                      |
|                          | OCTOPUSSY 1500 EVO | OIL&STEEL SPA                                   |
|                          | GOLDLIFT 14,70 LITHI | HINOWA SPA                                 |
| **GARDENING MACHINES**   |               |                                                   |
| Bush cutters             | STIHL FR 480 | ANDREAS STIHL SPA                                |
|                          | PREMIUM BCF 420/453 BP ERGO | OLEO-MAC (EMAK SPA GROUP)                          |
|                          | RM 410ES/510ES | CORMIK SPA                                        |
| Gardening off-road vehicles | PK 600     | GRILLO SPA                                       |
|                          | 200 DK 4X4   | ALKE’                                            |
|                          | TIGERCAR     | ANTONIO CARRARO SPA                              |
|                          | TIGERCAR PLUS | ANTONIO CARRARO SPA                              |
| Mowers with central/lateral rod | 630 WS MAX | BCS SPA                                          |
|                          | ACF 202      | ADRIATICA MACCHINE AGRICOLE SRL                  |
|                          | 220D         | GIANNI FERRARI SRL                               |
| Lawn clippers with driver seated | CLIMBER 7.10 | GRILLO SPA                                       |
|                          | SP 4400 HST | ANTONIO CARRARO SPA                              |
|                          | MA.TRA 205  | BCS SPA                                          |
| Golf trolleys            | TORO         | ALKE’                                            |
|                          | KUDO 6022K  | T.G.S. TECNO GOLF SERVICE SRL                    |
| **STREET CLEANING MACHINES** |           |                                                   |
| Compacters               | MINICOMPACTERS | POR.CELLI SRL                                    |
|                          | CM 1900 HYBRID | OMB INTERNATIONAL SRL                           |
|                          | VOLVO FE HYBRID | VOLVO TRUKS                                    |
| Street cleaners          | DULEVO       | DULEVO INTERNATIONAL SPA                         |
|                          | PATROL       | RCM SPA                                          |
|                          | 360 ELECTRIC | U.C.M. (UNIECO) SRL                              |
| Leaves blowers/fans      | STIHL BGE 71 AND 81 | ANDREAS STIHL SPA                               |
|                          | BV 162       | OLEO-MAC (EMAK SPA GROUP)                        |
| **AGRICULTURAL MACHINES** |           |                                                   |
| Harvest and pruning carts | ZIP25/CARRIER/SENIOR | BLOSI SNC                                        |
|                          | M9.S.COMPACT/HF3000 | F.LLI FESTI                                   |
| Self propelled sprinklers | IBIS 1500 LM | MAZZOTTI SRL                                     |
|                          | SERIES GK   | GRIM SRL                                         |
|                          | GRIMAC JR   | BARGAM SPA                                       |
| Crawler and/or wheel tractors | AGROLUX 310/320 | SAME DEUTZ-FAHR ITALIA                       |
|                          | SUPER TIGER 5500 | ANTONIO CARRARO SPA                             |
|                          | VP3600 GE   | ARGO TRACTORS SPA - VALPADANA                    |
| Help machines                                                                 | ELEKTROTRANS 800 | OELLE COSTRUZIONI MECCANICHE SRL |
|------------------------------------------------------------------------------|------------------|----------------------------------|
|                                                                              | ECOGREENITALIA   | LEOZANN SRL                      |
|                                                                              | CARRYALL 232 ELECTRIC | ANTONIO CARRARO SPA              |
|                                                                              | CLIMB CART 108 E 800-R4 | ESSEP.TECNO DI SASIA & C         |
| EARTH-MOVING MACHINES                                                        | 6.23B/1.33B      | VF VENIERI SPA                   |
| Rubberized terms                                                             | PB30/PB50/PB70   | PALAZZANI INDUSTRIE SPA          |
|                                                                              | E265             | SAMPIERANA SPA                   |
| Mini excavators (< 4 tons)                                                   | M22U             | F.LLI MESSERSI SPA               |
|                                                                              | ES150.5SR/ES300SR | SAMPIERANA SPA                   |
|                                                                              | 218 SV/224S      | CAMS MACCHINE S.A. (EX LIBRA)    |
| Skid Loader (compact blades)                                                 | SL35/SL45        | F.LLI MESSERSI SPA               |
|                                                                              | SK130.4/SK150.4  | SAMPIERANA SPA                   |
|                                                                              | CL35/CL45        | IMER INTERNATIONAL SPA           |
|                                                                              | 755              | CAMS MACCHINE S.A. (EX LIBRA)    |
| Rubberized blades (< 1 m³)                                                   | 263B PLUS        | VF VENIERI SPA                   |
|                                                                              | PL145            | PALAZZANI INDUSTRIE SPA          |
|                                                                              | AL250/AL45       | FIORI SPA                        |
| Mini crawler crane                                                           | SPD265C/SPD360C  | ORMET SPA (IMAI)                 |
| HORTICULTURE AND GREENHOUSES MACHINES                                        | STAR 3000        | GOLDONI SPA                      |
|                                                                              | TRX 9800         | ANTONIO CARRARO SPA              |
| Motor-cultivators                                                            | MTC 621          | MECCANICA BENASSI SPA            |
|                                                                              | 410              | EMAK SPA BERTOLINI               |
|                                                                              | G 45             | GRILLO SPA                       |
| Motor-hoes                                                                   | RL 308           | MECCANICA BENASSI SPA            |
|                                                                              | MZ 2100 R        | EMAK SPA                         |
|                                                                              | 12000            | GRILLO SPA                       |
| Scissors/shakers                                                             | LIXION/SELION    | PELLENC ITALIA SRL               |
|                                                                              | ALICE            | CAMPAGNOLA SRL                   |
| SNOW MACHINES                                                                | TROOPER          | LEITNTER TECHNOLOGIES SPA        |
| Snow-cats                                                                    | LYNX XTRIM SC 600 H.O. E-TEC | LEITNTER TECHNOLOGIES SPA        |
## ANNEX 3

Main characteristics of the battery pack for the vehicles considered in the study

| Model or type                  | Energy  | Composition | Cost (400 €/kWh) | Weight (100 Wh/kg) | Volume (150 Wh/l) |
|-------------------------------|---------|-------------|------------------|--------------------|-------------------|
| **BUILDING SITES MACHINES**   |         |             |                  |                    |                   |
| P 25.6                        | 35      | 16x12V/180Ah| 14000            | 350                | 233               |
| MLT 731 Turbo                  | 35      | 16x12V/180Ah| 14000            | 350                | 233               |
| LM1330/LM133                  | 35      | 16x12V/180Ah| 14000            | 350                | 233               |
| Rossetto TRV 10                | 9       | 4x12V/180Ah | 3600             | 90                 | 60                |
| HS 400 (electric)              | 9       | 4x12V/180Ah | 3600             | 90                 | 60                |
| Series 50                     | 9       | 4x12V/180Ah | 3600             | 90                 | 60                |
| Cingo M 10.2 plus              | 35      | 24x12V/120Ah| 14000            | 350                | 233               |
| Merlo Cingo M 6.2 plus         | 9       | 4x12V/180Ah | 3600             | 90                 | 60                |
| C 12.65                       | 6       | 4x12V/120Ah | 2304             | 58                 | 38                |
| Octopusy 1500 evo              | 6       | 4x12V/120Ah | 2304             | 58                 | 38                |
| Goldlift 14,70 Lithium         | 6       | 4x12V/120Ah | 2304             | 58                 | 38                |
| **EARTH MOVING MACHINES**      |         |             |                  |                    |                   |
| 6.23B/1.33B                   | 35      | 16x12V/180Ah| 14000            | 350                | 233               |
| pb30/pb50/pb70                | 35      | 16x12V/180Ah| 14000            | 350                | 233               |
| E265                          | 35      | 16x12V/180Ah| 14000            | 350                | 233               |
| M22U                          | 17      | 8x12V/180Ah | 7000             | 170                | 113               |
| ES150.5SR/ES300SR              | 17      | 8x12V/180Ah | 7000             | 170                | 113               |
| 218 SV/224S                   | 17      | 8x12V/180Ah | 7000             | 170                | 113               |
| SL35/SL45                     | 17      | 8x12V/180Ah | 7000             | 170                | 113               |
| SK130.4/SK150.4               | 17      | 8x12V/180Ah | 7000             | 170                | 113               |
| CL35/CL45                     | 17      | 8x12V/180Ah | 7000             | 170                | 113               |
| 755                           | 17      | 8x12V/180Ah | 6800             | 170                | 113               |
| 263B Plus                     | 35      | 16x12V/180Ah| 14000            | 350                | 233               |
| PL145                         | 35      | 16x12V/180Ah| 14000            | 350                | 233               |
| AL250/AL450                   | 35      | 16x12V/180Ah| 14000            | 350                | 233               |
| **STREET CLEANING MACHINES**   |         |             |                  |                    |                   |
| MINICOMPACTER                 | 17      | 8x12V/180Ah | 7000             | 170                | 113               |
| DULEVO                        | 35      | 16x12V/180Ah| 14000            | 350                | 233               |
| Patrol                        | 35      | 24x12V/120Ah| 14000            | 350                | 233               |
| 360 electric                  | 17      | 8x12V/180Ah | 6800             | 170                | 113               |
| **GARDENING MACHINES**        |         |             |                  |                    |                   |
| PK 600                        | 9       | 4x12V/180Ah | 3600             | 90                 | 60                |
| 200 DK 4x4                    | 9       | 4x12V/180Ah | 3600             | 90                 | 60                |
| Tigercar                      | 9       | 4x12V/180Ah | 3600             | 90                 | 60                |
| Tigercar plus                 | 9       | 4x12V/180Ah | 3600             | 90                 | 60                |
| 630 WS MAX                    | 6       | 4x12V/120Ah | 2304             | 58                 | 38                |
| ACF 202                       | 6       | 4x12V/120Ah | 2304             | 58                 | 38                |
| 220D                          | 35      | 16x12V/180Ah| 14000            | 346                | 230               |
| Climber 7.10                  | 17      | 8x12V/180Ah | 7000             | 173                | 115               |
| SP 4400 HST                   | 35      | 16x12V/180Ah| 14000            | 350                | 233               |
| MA.TRA 205                    | 17      | 8x12V/180Ah | 7000             | 173                | 115               |
| TORO                          | 9       | 4x12V/180Ah | 3600             | 90                 | 60                |
| Kudo 6022K                    | 9       | 4x12V/180Ah | 3456             | 86                 | 58                |
| **AGRICULTURAL MACHINES**     |         |             |                  |                    |                   |
| ZIP25/Carrier/Senior           | 17      | 8x12V/180Ah | 7000             | 173                | 115               |
| M9 s.compact/HF3000            | 17      | 8x12V/180Ah | 7000             | 173                | 115               |
| IBIS 1500 LM                  | 35      | 16x12V/180Ah| 14000            | 350                | 233               |
| Model                  | Series | Voltage/Amphours | Current (A) | Voltage (V) | RPM |
|------------------------|--------|-----------------|-------------|-------------|-----|
| Series GK              | 35     | 16x12V/180Ah    | 14000       | 350         | 233 |
| Grimac JR              | 35     | 16x12V/180Ah    | 14000       | 350         | 233 |
| Agrolux 310/320        | 35     | 16x12V/180Ah    | 14000       | 350         | 233 |
| Super tiger 5500       | 35     | 16x12V/180Ah    | 14000       | 350         | 233 |
| VP3600 GE              | 35     | 16x12V/180Ah    | 14000       | 350         | 233 |
| Elektrotrans 800       | 6      | 4x12V/120Ah     | 2304        | 58          | 38  |
| Ecogreenitalia         | 6      | 4x12V/120Ah     | 2304        | 58          | 38  |
| Carryall 232 Electric  | 6      | 4x12V/120Ah     | 2304        | 58          | 38  |
| Climb Cart 108 E 800-R4| 6      | 4x12V/120Ah     | 2304        | 58          | 38  |
| HORTICULTURE AND       |        |                 |             |             |     |
| GREENHOUSES MACHINES   |        |                 |             |             |     |
| STAR 3000              | 17     | 8x12V/180Ah     | 7000        | 170         | 113 |
| TRX 9800               | 35     | 16x12V/180Ah    | 14000       | 350         | 233 |
| MTC 621                | 9      | 4x12V/180Ah     | 3600        | 90          | 60  |
| 410                    | 9      | 4x12V/180Ah     | 3600        | 90          | 60  |
| G 45                   | 9      | 4x12V/180Ah     | 3600        | 90          | 60  |
| RL 308                 | 6      | 4x12V/120Ah     | 2304        | 58          | 38  |
| MZ 2100 R              | 6      | 4x12V/120Ah     | 2304        | 58          | 38  |
| 12000                  | 6      | 4x12V/120Ah     | 2304        | 58          | 38  |
| SNOW MACHINES          |        |                 |             |             |     |
| Lynx Xtrim SC 600 H.O. E-TEC | 35 | 16x12V/180Ah    | 14000       | 350         | 233 |
ANNEX 4

BMS specifications of the demonstrators

| Function            | Note                                                      |
|---------------------|-----------------------------------------------------------|
| Protection          | Two levels: warning and alarm                            |
| Balancing           | To define if active or passive, if only at the end of charge |
| Charge control      |                                                           |
| SOC calculation     |                                                           |
| Data acquisition    | Settable frequency, max. 10 Hz                            |
| Data communication  |                                                           |

BMS Specifications:
monitored and registered variables

| SOC                            |                                      |
|--------------------------------|--------------------------------------|
| Global current                 |                                      |
| Module current                 |                                      |
| Module voltage                 |                                      |
| Cell voltage                   |                                      |
| Minimum cell voltage           |                                      |
| Maximum cell voltage           |                                      |

Characteristics of the battery system

| Parameter                        | Value | Unit | Note                     |
|----------------------------------|-------|------|--------------------------|
| Capacity                         | 100   | Ah   |                          |
| Nominal voltage                  | 51.2  | V    |                          |
| Maximum voltage                  | 61.6  | V    | Overvoltage alarm        |
| Minimum voltage                  | 40    | V    | Undervoltage alarm       |
| N. of cells parallel connected in each module | 0 #   |      |                          |
| N. of cells series connected in each module | 4 #   |      |                          |
| N. of modules parallel connected | 0 #   |      |                          |
| N. of modules series connected   | 4     |      |                          |
| Max. continuous discharge current| 300   | A    |                          |
| Peak discharge current           | 500   | A    | Overcurrent alarm        |
| Discharge Current peak duration  | 60    | s    |                          |
| Max. continuous charge current   | 100   | A    |                          |
| Working temperature (min)        | -10   | °C   | Undertemperature alarm   |
| Working temperature (max.)       | +55   | °C   | Overtemperature alarm    |
### Cell characteristics

| Parameter            | Value           | Unit | Note                   |
|----------------------|-----------------|------|------------------------|
| Manufacturer         | HIPOWER         |      |                        |
| Model                | HP-PW-100AH     |      |                        |
| Chemistry            | LiFePO₄         |      |                        |
| Capacity             | 100             | Ah   |                        |
| Charge voltage (Max) | 3.85            | V    | Overvoltage alarm      |
| Nominal voltage      | 3.2             | V    |                        |
| Cut-off voltage (Min)| 2.5             | V    | Undervoltage alarm     |

### BMS specifications: communication I/O

| Parameter                  | Value      | Unit     | Note     |
|----------------------------|------------|----------|----------|
| Type                       | CAN bus    |          |          |
| Speed                      | 125 / 250  | kbps     |          |
| Charge reserve output (SOC)| Y          | Y/N      |          |
| Thermal management output  | Y          | Y/N      |          |

### Power electronics

| Parameter                  | Value | Unit | Note   |
|----------------------------|-------|------|--------|
| Mani contactor for battery disconnection | Y     | Y/N  |        |

### BMS specifications: charge control

| Parameter             | Value | Unit | Note |
|-----------------------|-------|------|------|
| Charge power          | 5000  | W    |      |
| Max. charge current   | 100   | A    |      |
| Type of control       | CAN   |      |      |