EVS26
Los Angeles, California, May 6-9, 2012

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: $LiFePO_4$ 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, $LiFePO_4$

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.

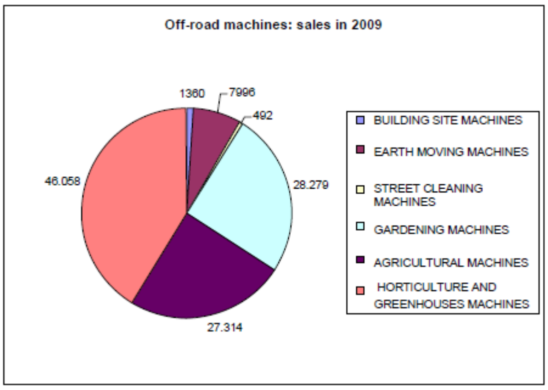

Figure 1: Italian market of off-road vehicles: sales in 2009

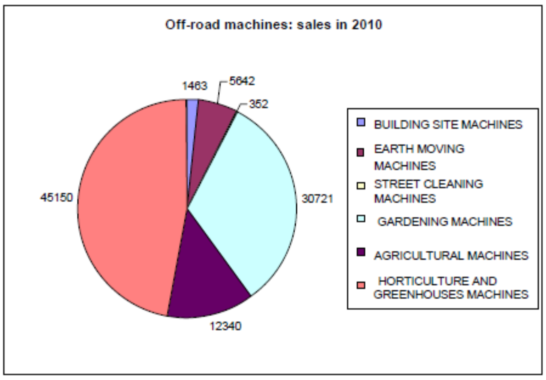

Figure 2: Italian market of off-road vehicles: sales in 2010

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.

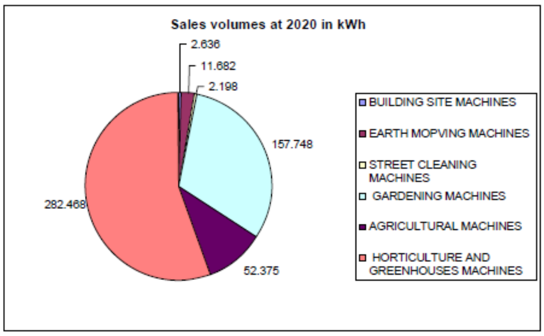

Figure 3: Potential sales volume of off-road vehicles at 2020 for different sectors

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.

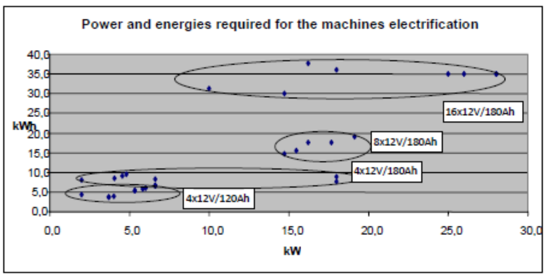

Figure 4 – Distribution of power and energy for the electrifications of off-road vehicles

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 hypothetic 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%.

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

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.

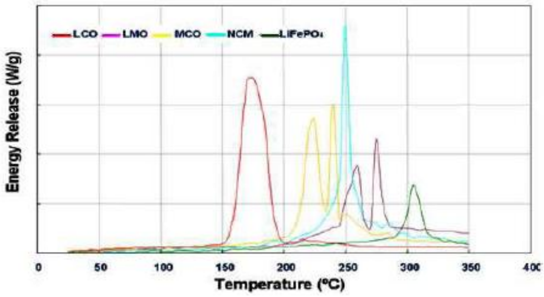

Figure 6: Energy released at various temperatures for the different cathode materials

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.

Table. 1: History of recent purchases of lithium ion batteries at ENEA

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	
cell	LFP	3,2V 30/60/ 100Ah	276	May 2011	

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		
3.7	1.8	3.18	477.477	LCO	K
3.2	0.6	7.74	4031.25	LFP	K
3.7	1.95	10.32	1430.35	?	P
3.2	1.4	4.76	1062.5	LFP	K
3.2	1.25	6.34	1585	LFP	K
3.7	2	6.15	831.081	LCO	K
3.3	2.3	14.55	1916.99	LFP	A
3.2	3	7.93	826.047	LFP	K
3.2	3.2	9.13	891.601	LFP	K
3.2	2.5	10.32	1290	LFP	K
3.6	50	129.26	718.111	LCO	T
3.2	40	53.99	421.796	LFP	T
12.8	16	197.68	965.234	LFP	K
3.2	50	98.44	615.25	LFP	B
12	10	198.48	1654	LFP	L
3.6	90	232.66	718.086	LCO	T
3.2	60	80.98	421.770	LFP	T
3.74	100	528.74	1413.74	NMC	O
3.6	100	258.52	718.111	LCO	T
3.2	90	121.47	421.770	LFP	T
3.2	100	178.63	558.218	LFP	B
12	20	373.13	1554.70	LFP	L
24	10	396.95	1653.95	LFP	L
3.6	200	517.03	718.097	LCO	T
3.2	160	215.94	421.757	LFP	T
12	30	547.79	1521.63	LFP	L
36	10	595.43	1653.97	LFP	L
3.2	200	317.56	496.187	LFP	T
12.8	42	682.76	1270.01	LFP	V
3.2	200	364.4	569.375	LFP	B
12	40	722.45	1505.10	LFP	L
24	20	746.27	1554.72	LFP	L
48	10	793.9	1653.95	LFP	L
12	60	1095.9	1521.65	LFP	L
24	30	1095.5	1521.65	LFP	L
36	20	1119.4	1554.72	LFP	L
72	10	1190.8	1653.95	LFP	L
3.2	400	635.12	496.187	LFP	T
3.6	600	2326.6	1077.14	LCO	T
19.2	68	1536.2	1176.62	LFP	V
12.8	100	1508.4	1178.45	LFP	V
12	80	1444.9	1505.10	LFP	L
24	40	1444.9	1505.10	LFP	L
48	20	1492.5	1554.72	LFP	L
96	10	1587.8	1653.96	LFP	L
12.8	122	1841.8	1179.46	LFP	V
108	10	1786.2	1653.96	LFP	L
36	30	1643.3	1521.64	LFP	L
12	120	2167.3	1505.10	LFP	L
144	10	2381.7	1653.96	LFP	L
24	60	2191.1	1521.64	LFP	L
36	40	2167.3	1505.10	LFP	L
48	30	2191.1	1521.64	LFP	L
3.2	800	1587.81	620.238	LFP	T

In Table 2, where a comparison between the cost of lithium ion batteries of various technologies (LiFePO4, 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

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 $LiFePO_4$ 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 $LiFePO_4$. 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 lighting 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.

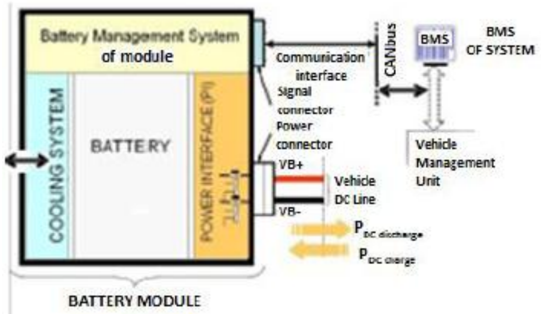

Figure 7: Preliminary scheme of the battery module with BMS

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).

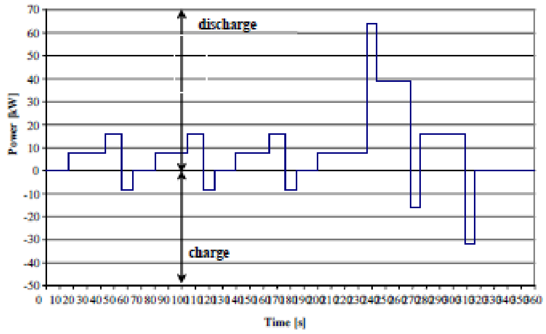

Figure 8: Profile for thermal study

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

Table 5: Power set-up and the length of the single steps for the thermal profile

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 (fs), 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 fs will be 3).

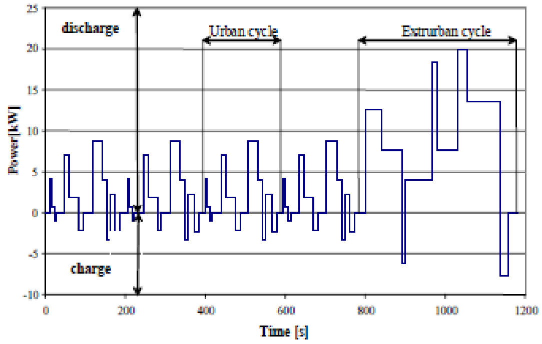

Figure 9 – ECE cycle

Table 6 and 7 show the power set up and the length of the single steps of the test profile.

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

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 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

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	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

Specific		Value
Voltage [V]		3.20
Nominal capacity [Ah]		60
Dimensions, terminals enclosed (L*W*H) [mm]		114x61x203
Weight [kg]		2.04
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. cont. current [A]	60
	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 11.

Table 11: Main electric characteristics of the medium size standard module for electric off-road vehicles

Nominal voltage [V]		12.80
Nominal capacity [Ah]		60
Minimum weight [kg]		8.2
Maximum specific energy [Wh/kg]		94
Maximum energy density [Wh/l]		136
Discharge @ +23 °C	Max. cont. current [A]	180
	Peak @ 60 sec [A]	300
	Cut - off [V]	10
Charge @ +23 °C	Charge method	CC/CV (14.6 V)
	Max. cont. current [A]	60
	Cut – off	15.4 V

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

Specific		Value
Nominal voltage [V]		12.80
Nominal capacity [Ah]		100
Dimensions, terminals enclosed (L*W*H) [mm]		163x51x278
Weight [kg]		3.40
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

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

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

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 ÷ 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.

Figure 10 – Off-road vehicle ATX 200E

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

Motor	Type	electric
	Nominal supply voltage [VDC]	48
	Power [kW]	6
	Power peak [kW]	17,5
Batteries	Quantity [n]	8
	Nominal voltage [VDC]	6
	Capacity [Ah]	190
	Recharge [h]	8
Weight (when empty) [kg]		820
Load capacity [kg]		530
Tow capacity [kg]		2000
Max. speed [km/h]		30
Range [km]		70

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

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[1]
		326 x 408 x 278[2]
Minimum weight[3] [kg]		54.4
Max. specific energy [Wh/kg]		94
Max. energy density [Wh/l]		138
Discharge @ +23 °C	Max. cont. current [A]	300
	Peak @ 60 sec [A]	500
	Cut - off [V]	40
Charge @ +23 °C	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

[1] First hypothesis of positioning the cells.
[2] Second hypothesis of positioning the cells.
[3] Weight of the cells only.

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.

Acknowledgments

This work is supported by the Italian Ministry of Economic Development in the framework of the Program Agreement for the Research on Electric System. The scientific and technical assistance and collaboration of the University of Pisa are also acknowledged.

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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 dm^3
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 LITHIUM	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
Lawn clippers with driver seated	220D	GIANNI FERRARI SRL
	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
	SUPERTIGER 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		
Rubberized terns	6.23B/1.33B	VF VENIERI SPA
	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 m^3)	263B PLUS	VF VENIERI SPA
	PL145	PALAZZANI INDUSTRIE SPA
	AL250/AL450	FIORI SPA
Mini crawler crane	SPD265C/SPD360C	ORMET SPA (IMAI)
HORTICULTURE AND GREENHOUSES MACHINES		
Horticulture tractors	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		
Snow-cats	TROOPER	LEITNER TECHNOLOGIES SPA
Motor-sledges	LYNX XTRIM SC 600 H.O. E-TEC	LEITNER TECHNOLOGIES SPA

ANNEX 3

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

Model or type	Energy [kWh]	Composition	Cost (400 €/kWh)	Weight (100 Wh/kg) [kg]	Volume (150 Wh/l) [l]
BUILDING SITES MACHINES					
P 25.6	35	16x12V/180Ah	14000	350	233
MLT 731 Turbo	35	16x12V/180Ah	14000	350	233
LM1330/LM1333	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
Octopussy 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
SPD265C/SPD360C	9	4x12V/180Ah	3600	90	60
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

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
Supertiger 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			0	0	0
Lynx Xtrim SC 600 H.O. E-TEC	35	16x12V/180Ah	14000	350	233

ANNEX 4

BMS specifications of the demonstrators

BMS specifications: functions

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	$LiFePO_4$		
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		