Journal of Power Sources 196 (2011) 9574–9578

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Short communication

# Impact of charging efficiency variations on the effectiveness of variable-rate-based charging strategies for electric vehicles

Francesco A. Amoroso, Gregorio Cappuccino*

*Department of Electronics, Computer Science and Systems, University of Calabria, Via P. Bucci, 42C, 87036-Rende (CS), Italy*

ARTICLE INFO

*Article history:*
Received 17 February 2011
Received in revised form 20 July 2011
Accepted 23 July 2011
Available online 29 July 2011

*Keywords:*
Electric vehicles
Smart battery charger
Charging efficiency
Variable rate charging
Smart grid

ABSTRACT

The huge energy demand coming from the increasing diffusion of plug-in electric vehicles (PEVs) poses a significant challenge to electricity utilities and vehicle manufacturers in developing smart charging systems interacting in real time with distribution grids.

These systems will have to implement smart charging strategies for PEV batteries on the basis of negotiation phases between the user and the electric utility regarding information about battery chemistries, tariffs, required energy and time available for completing the charging. Strategies which adapt the charging current to grid load conditions are very attractive. Indeed, they allow full exploitation of the grid capacity, with a consequent greater final state of charge and higher utility financial profits with respect to approaches based on a fixed charging rate.

The paper demonstrates that the charging current should be chosen also taking into account the effect that different charging rates may have on the charging efficiency. To this aim, the performances of two smart variable-rate-based charging strategies, taken as examples, are compared by considering possible realistic relationships between the charging efficiency and the charging rate. The analysis gives useful guidelines for the development of smart charging strategies for PEVs as well as for next-generation battery charging and smart grid management systems.

## 1. Introduction

Plug-in electric vehicles (PEVs) are expected to have a rapid diffusion over the next few years. The potential advantages deriving from PEVs use are huge: lower operational costs, greater driving comfort and often better acceleration performance compared with traditional gasoline cars. However, probably the most important advantage is the reduced environmental impact due to the abatement of volatile pollutants, contributing, together with the use of renewable resources for energy production, to effectively reducing global warming [1].

Typically, PEVs require 0.2–0.3 kWh for a mile of driving and are characterized by battery capacity values in the range of 8–55 kWh. The additional demand for electric power required to charge a large fleet of PEVs may lead to extra large and undesirable peaks in electrical consumption. In fact, according to the results of an analysis carried out by the Joint Research Centre of the European Commission for a real case study, the maximum electric power request would increase by about 30% if PEVs should reach 25% of the vehicle fleet [2].

Unfortunately, the increase in the grid load due to PEVs can cause instabilities and interruptions. For example, a recent analysis performed for a typical medium-voltage distribution grid, showed that the line losses coming from the absence of any charging regulation mechanism could lead to exceeding the lower limit allowed for the line voltage even for a PEV penetration level higher than 10% [3]. To avoid grid overload problems, smart scheduling strategies for the charging processes of PEVs are increasingly gaining attention [5–11]. The implementation of these strategies will require a smart grid infrastructure capable of communicating with battery chargers and coordinating the charging processes of plugged in PEVs. Interestingly, this smart grid will enable also the possibility of using batteries of PEVs to inject energy into the grid in the cases of grid faults or to regulate the voltage line frequency [1]. These key aspects, along with the possibility of achieving both an effective exploitation of renewable resources and a significant reduction of the global energy consumption, has made the creation of smart grids one of the crucial priorities for governments in order to reduce $CO_2$ emissions, as well as one of the most important research topics for both the scientific community and the industry [1–4].

In order to identify effective energy dispatching strategies for PEVs, it is fundamental to distinguish between two possible scenarios. On the one hand, there will be the necessity to provide customers with ad hoc high-power charging stations allowing a

---

* Corresponding author. Tel.: +39 0984494769; fax: +39 0984494834.
*E-mail address:* cappuccino@unical.it (G. Cappuccino).

0378-7753/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2011.07.074

**Table 1**
User profiles.

| User | $E_{R0}$ (kWh) | $P_{MAX}$ (kW) | $P_{MIN}$ (kW) | $T_A$ (h) | $T_D$ (h) | $K_U$ (€ kWh$^{-1}$) | $K_F$ (€ kWh$^{-1}$) |
|---|---|---|---|---|---|---|---|
| 1 | 15 | 15 | 1.5 | 0 | 4 | 0.10 | 0.05 |
| 2 | 18 | 18 | 1.8 | 0.25 | 3 | 0.10 | 0.05 |
| 3 | 25 | 25 | 2.5 | 0.5 | 2 | 0.30 | 0.15 |
| 4 | 25 | 25 | 2.5 | 1 | 4 | 0.10 | 0.05 |
| 5 | 10 | 10 | 1.0 | 1.5 | 3.5 | 0.25 | 0.125 |
| 6 | 25 | 25 | 2.5 | 2 | 3 | 0.30 | 0.15 |

very fast PEV charging when necessary, for example in the case of a long trip.

In this case, the main goal is to satisfy the user charging request as soon as possible by performing the battery charging process in the smallest amount of time (reasonably in the order of 10 min), with practically no leeway in the decision of the usable charging rate, which should be as high as possible.

On the other hand, the typical daily usage of cars suggests that the fast charging option will not be strictly necessary in most real situations, in which it will be sufficient for customers to charge their PEVs when they come home or during work hours in which their PEVs are parked [1–3,8]. It is worth noting that, despite the longer available time to complete the charging process, it is estimated that also in these situations the occurrence of multiple charging requests concentrated in a limited time period will have a strong impact on the grid load with high numbers of PEVs. Nevertheless, differently from the fast charging scenario discussed above, the main goal in this second scenario is not to perform the battery charging process as soon as possible, but just within the expected departure time of the user. This allows a greater flexibility in determining an effective energy dispatching strategy with the aim of avoiding grid overload. A promising strategy is the use of variable charging rates to adapt the power drawn by the charger from the grid to the global load conditions, in order to exploit the grid capability fully and to guarantee a high degree of user satisfaction [8,10]. However, the development of effective charging strategies needs to take into account several technological and economic aspects. One of these is the charging efficiency, i.e. the ratio between the energy stored in the battery and the energy supplied by the grid. In previous works dealing with energy dispatching strategies for PEVs, a constant charging efficiency not-dependent on the charging rate was assumed [6,8,11]. However, the efficiency of real charger/battery systems is typically determined by the charging rate [12,13]. In this letter, the impact of variable charging efficiency on the effectiveness of charging strategies is investigated. Two possible variable rate-based charging algorithms are considered as examples and their performance is compared in both the case of constant and variable efficiency profiles. The two strategies are introduced in Section 2, in which the advantages of variable-rate-based with respect to fixed-rate-based charging approaches are also shown; the impact of the dependence between charging efficiency and charging rate on the performance of the two considered strategies is analyzed in Section 3; finally, statistical analysis of a large-scale system and conclusions are reported in Section 4.

## 2. Variable-rate-based charging strategies

With the aim of clearly introducing the problem, a simple situation is firstly presented by considering the evolution of a grid node in the presence of six vehicles in a period of 4 h (0–4 h). A constant available power of 30 kW is considered for the sake of simplicity and without loss of generality in the analysis, which can be easily extended to the case of variable available power profiles caused by different existing grid load values with time. The problem was formulated by taking into account the following parameters for each user:

- $E_{R0}$: total energy required to charge the battery up to the desired level (in kWh);
- $P_{MAX}$: maximum power (in kW) that the battery can absorb during the charging process (related to the maximum admissible charging current);
- $P_{MIN}$: minimum power (in kW) that the battery can absorb during the charging process (related to the minimum admissible charging current);
- $T_A$: arrival time (in h) of the user in the system;
- $T_D$: departure time (in h) of the user from the system;
- $K_U$: electricity rate paid by the user (in € kWh$^{-1}$);
- $K_F$: penalty (in € kWh$^{-1}$) the grid manager must pay to the user in case some of the requested energy cannot be delivered to the user by the grid.

The system performance was evaluated by measuring both the satisfaction of each user and the financial profit of the utility. To this aim, the following parameters are defined:

- $E_A$: energy allocated to the user (in kWh) at the end of the process;
- $E_R$: additional energy required to complete charging process. It is calculated as $E_R = E_{R0} - E_A$;
- $E_{US}$: actual amount of energy (in kWh) that the user can utilize at the end of the process. It is calculated as $E_{US} = \eta E_A$, $\eta$ being the efficiency of the charging process;
- $SD$: satisfaction degree of the user (in %). It is calculated as $SD = (E_{US}/E_{R0})\,100$;
- $PR$: profit for the utility (in €). It is calculated as $PR = K_U E_A - K_F E_R$.

Table 1 reports the profiles of the six users, in which $P_{MAX}$ and $P_{MIN}$ are assigned assuming a maximum and a minimum charging rate of 1 C and 0.1 C, respectively, C being the battery capacity. The user tariffs and penalties were determined by considering typical electricity costs in Europe, which range from about 0.1€ to about 0.3 € kWh$^{-1}$ [16]. In particular, they were fixed in order to simulate a reasonable scenario in which users who have less time at their disposal to complete the charging process are willing to pay a higher tariff for the service, with a larger penalty for the utility in the case of poor quality of service.

First, the charging processes were managed by using the basic approach indicated as "Fixed-Rate First-Come-First-Served" (FR-FCFS). In this approach, the charging process of each user is performed at a fixed rate, corresponding to the maximum charging rate admissible for its vehicle battery. Moreover, the charging process of each user starts when the vehicle is plugged-in, provided that the grid is capable of allocating the power required. The analysis was initially carried out by considering a charging efficiency $\eta = 1$. MATLAB simulation results related to the satisfaction degrees of each user are summarized in Table 2. As noticeable, four users leave the systems after being fully charged, but two users are completely dissatisfied. This results in an average satisfaction degree (calculated as the mean value of the satisfaction degree of each user) of 67%, and in a total financial profit for the utility of just 0.8€ (Table 3). The disadvantages of the FR-FCFS approach can be further appreciated by considering the plot in Fig. 1, which shows the trend of the total allocated power during the 4-h time period.

**Table 2**
User satisfaction degrees with unitary efficiency.

| User | Satisfaction degree (%) | | |
|---|---|---|---|
| | FR-FCFS | MEWP | SEWP |
| 1 | 100 | 100 | 100 |
| 2 | 100 | 84.7 | 97.2 |
| 3 | 0 | 100 | 100 |
| 4 | 100 | 100 | 100 |
| 5 | 100 | 100 | 100 |
| 6 | 0 | 87.5 | 80.3 |

**Table 3**
Average satisfaction degree and total profit.

| | Average satisfaction degree (%) | Total profit (€) |
|---|---|---|
| FR-FCFS | 67.0 | 0.8 |
| MEWP | 95.4 | 21.4 |
| SEWP | 96.3 | 22.6 |

It appears that the potentialities of the grid are strongly underexploited, the total allocated power being significantly less than the maximum available power for the greater part of the entire process. Thus, the FR-FCFS approach is practically unusable to solve the problem, which can be instead conveniently managed by using algorithms which exploit variable charging rates and schedule the different charging processes on the basis of the user priorities.

Two different variable rate charging approaches are used as examples. This does not limit the general validity of the discussion presented in the following, which can be extended to any other scheduling strategy. In both the considered strategies, users are ordered in decreasing priority, and the energy is allocated at a given charging rate to users with the highest priority until the power available from the grid is exhausted. In general, the user priority changes with time. In fact, both the time at disposal and the amount of energy still required to complete the battery charging of each user change as the process evolves. For this reason, the entire window of observation of the process is divided into time slots of duration $\Delta t$ in which the user priorities are updated.

Obviously, the priority function is determined by the specific system performance of interest, therefore its definition is not univocal. In this work, the priority function ($G$) for each user is defined as follows:

$$\begin{cases} G = G_S + G_P; \quad G_S = \alpha_1 \dfrac{E_R(t)}{P_{AVMAX} \cdot T_R(t)} \\ G_P = \dfrac{E_R(t)}{P_{AVMAX} \cdot \Delta t} \left( \alpha_2 \dfrac{K_U}{K_{UMAX}} + \alpha_3 \dfrac{K_F}{K_{FMAX}} \right) \end{cases} \tag{1}$$

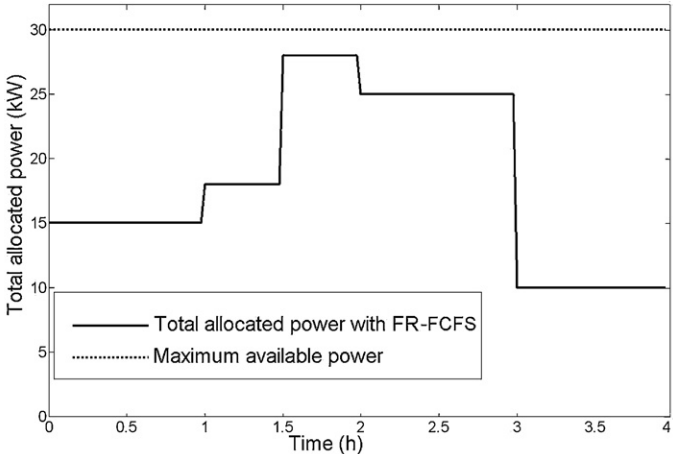

**Fig. 1.** Trend of the allocated power by using the FR-FCFS approach.

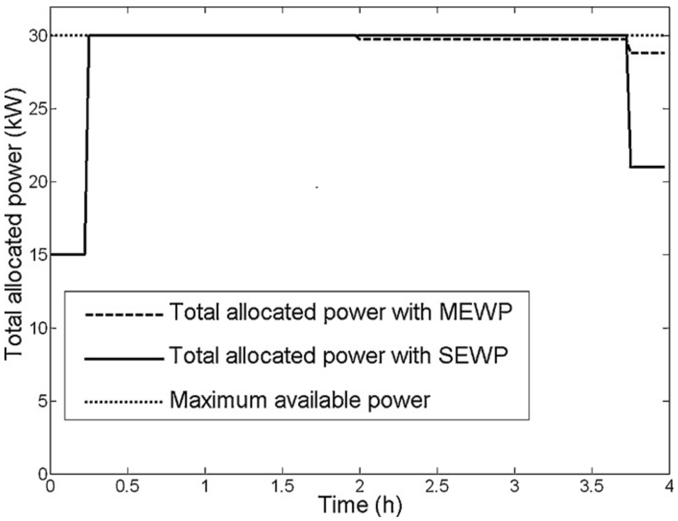

**Fig. 2.** Trend of the allocated power by using MEWP and SEWP approaches.

In (1), $E_R(t)$ is the energy still required to complete the charging process at the time instant $t$, $T_R(t)$ is the time which is still available before the user leaves the system, $P_{AVMAX}$ is the maximum available power from the grid, $K_{UMAX}$ and $K_{FMAX}$ are the maximum values admissible for $K_U$ and $K_F$, respectively, and $\alpha_1$, $\alpha_2$ and $\alpha_3$ are weighting coefficients. The priority function (1) is formulated to take into account both the user satisfaction and the utility profit by means of $G_S$ and $G_P$, respectively. In particular, $\alpha_1 = 0.5$ and $\alpha_2 = \alpha_3 = 0.25$ are fixed in order to balance the requirements in terms of degree of user satisfaction and utility profit, and to have $G = 1$ when the user is characterized by the maximum tariff and penalty (i.e. $K_U = K_{UMAX}$ and $K_F = K_{FMAX}$), and the power required to complete the charging process is equal to the maximum available power (i.e. $E_R(t)/T_R(t) = P_{AVMAX}$). Obviously, although the user priority function exceeds 1 when $E_R(t)/T_R(t) > P_{AVMAX}$, the maximum power which can be allocated to the user is limited to $P_{AVMAX}$.

The next step after the user priority evaluation is the definition of its assigned charging rate (indicated as $CR$). Two different strategies are considered herein to determine the charging rate of a user in a generic time slot. The first approach is called "Maximum Energy With Priority" (MEWP), and consists in allocating all the energy required by the user in order to complete his charging process by the end of the current time slot. In this case, the charging rate is given by the ratio between the energy still required by the user and the slot duration, i.e. $C_R = E_R(t)/\Delta t$. The second approach is called "Spread Energy With Priority" (SEWP), and consists in spreading the energy to be still supplied to the user over the entire time period available before the user leaves the system. In this case, the charging rate is calculated as $C_R = E_R(t)/T_R(t)$. Simulations were performed to evaluate the impact of the MEWP and SEWP approaches for the six vehicles of Table 1. As shown by results in Tables 2 and 3, the two smart approaches lead to a significant increase in both the degrees of user satisfaction and the total profit of the utility with respect to the FR-FCFS strategy because of a better exploitation of the grid potentiality. Fig. 2 clearly evidences that the total allocated power by using MEWP and SEWP is almost equal to the maximum power available from the grid for the greater part of the process. The comparison between data in Tables 2 and 3 shows that the MEWP and SEWP methods are almost equivalent when a unitary constant charging efficiency is assumed. In the next section, the impact of the charging efficiency will be analyzed.

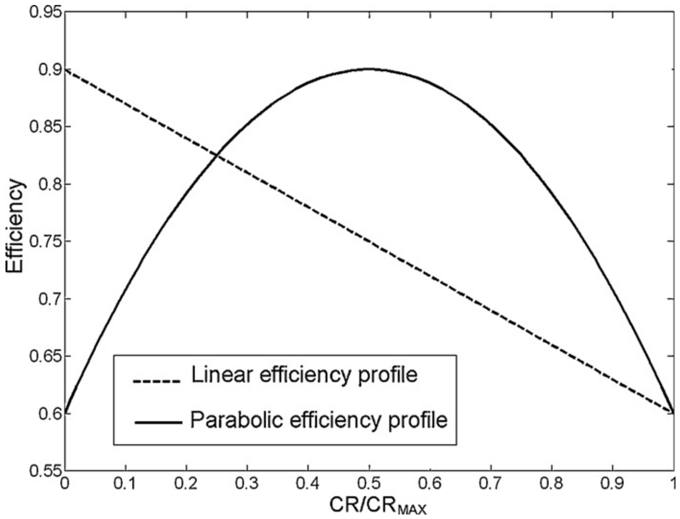

**Fig. 3.** Two possible charging efficiency profiles.

## 3. Impact of charging efficiency

The correct evaluation of the real effectiveness of a smart charging strategy requires taking into account carefully the energy losses in the charging process in order to estimate the energy actually stored into the battery at the end of the charging process.

The charging efficiency is usually considered as a constant, whose typical values are comprised between 0.6 and 0.9 [6,8,11,14]. However, this assumption is far from describing phenomena characterizing real charging processes, in which the efficiency strongly depends on the charging current [12,13].

Therefore, the efficiency profile (i.e. the relationship between charging efficiency and charging current) has to be considered for a coherent analysis of the performance of variable-rate-based strategies. This profile strongly depends on the specific battery technology and charger circuitry. In the following, the analysis will be carried out by assuming two possible realistic efficiency profiles in which the efficiency varies between 0.6 and 0.9 according to the ratio between the charging rate and the maximum value admissible for the battery charging rate ($CR_{MAX}$) (Fig. 3).

The two profiles of Fig. 3 are constructed by considering that the efficiency usually drops at high charging rates in real situations [12,13], essentially because of the increasing of power losses on the internal resistances of both the battery and the battery charger. On this basis, the first efficiency profile is simply assumed to be linearly decreasing with the charging rate.

For the sake of completeness, the second efficiency profile is instead assumed to be parabolic in order to take into account also possible efficiency drops at low charging rates which can occur in the battery charger [15,17].

Clearly, the assumption of the two generic efficiency profiles depicted in Fig. 3 does not limit the general validity of the analysis, which could be directly extended to any other specific profile characterizing the specific battery/battery charger system used.

In both the situations considered, the total profit of the utility remains unchanged with respect to the case of unitary efficiency, because the profit is calculated on the basis of the energy allocated to the user, which does not vary. Instead, the degree of satisfaction of each user changes, since it is determined by the energy which is actually usable by the users. Table 4 compares the average satisfaction degree of the users obtained by using the MEWP and SEWP methods in the presence of the two profiles considered. Differently from the previous case in which constant unitary charging efficiency was assumed (Table 3), the two strategies do not lead to similar average satisfaction degrees in the presence of the two variable charging efficiency profiles considered. In particular, it appears that the SEWP proves to be more suitable than the MEWP approach in the cases under examination. This is because the efficiency drops at high charging rates in both the efficiency profiles used, and the MEWP approach leads to using higher charging rates than the SEWP one on average (in the SEWP approach the energy allocated to the user is spread over the entire time period allowed for the user charging). As shown by the above example, the dependence of the charging efficiency on the charging rate may be a fundamental aspect to be taken into account in order to evaluate the actual effectiveness of variable-rate-based charging strategies aiming to find the most convenient solution for the PEVs charging problem.

**Table 4**
Average satisfaction degree with different efficiency profiles.

| | Average satisfaction degree (%) | | |
|---|---|---|---|
| | Unitary efficiency | Linear efficiency profile | Parabolic efficiency profile |
| MEWP | 95.4 | 60.9 | 63.4 |
| SEWP | 96.3 | 66.3 | 73.0 |

**Table 5**
Main statistical analysis results with different efficiency profiles.

| Average satisfaction degree (%) | | | | | |
|---|---|---|---|---|---|
| Unitary efficiency | | Linear efficiency profile | | Parabolic efficiency profile | |
| MEWP | 77.5 | MEWP | 47.0 | MEWP | 46.6 |
| SEWP | 79.5 | SEWP | 54.4 | SEWP | 57.6 |

## 4. Statistical analysis and conclusions

In order to investigate further the system performance in a large-scale scenario, the evolution of a portion of the grid characterized by a maximum available power of 6 MW during an 8-h period was also analyzed. Statistical simulations were performed for 10 different cases in which the arrivals of the users were modelled by using Poisson distributions with a mean value of 100 per 30 min, and random charging profiles were assumed. The analysis of the process was carried out by considering the three different efficiency profiles assumed in the previous analysis. The values of the utility profit obtained by using the SEWP and the MEWP approaches are 9210€ and 8811€, respectively.

Simulation results related to the average degree of user satisfaction in the different scenarios considered are summarized in Table 5. The data in the table evidence that, also in a large-scale scenario, although the two strategies show similar performances when a constant unitary efficiency is considered, the SEWP approach performs significantly better than the MEWP one in the presence of variable charging efficiency profiles.

As shown, taking into account the relationship between the charging efficiency and the charging rate is therefore crucial when aiming to develop effective variable-rate-based charging strategies.

The study, which has been carried out by comparing two strategies taken as examples, can be also applied in order to evaluate the real effectiveness of any other possible charging method. Thus, the analysis performed gives useful well-founded guidelines for the development of smart charging strategies for PEVs, as well as for next-generation battery charging and smart grid management systems.

## References

[1] A. Ipakchi, F. Albuyeh, IEEE Power and Energy Magazine 7 (2009) 52–62.

[2] A. Perujo, et al., Potential Impact of Electric Vehicles on the Electric Supply System, JRC European Commission Scientific and Technical Reports, 2009.
[3] J.A. Pecas Lopes, F. Joel Soares, P.M.R. Almeida, Proceedings of the IEEE, vol. 99, no. 1, January 2011, 2011, pp. 168–183.
[4] European Commission, Smart Grids: from innovation to deployment, Communication from the Commission to the European Parliament, the Council, The European Economic and Social Committee and the Committee of the Regions, April 2011, http://ec.europa.eu/energy/gas_electricity/smartgrids/doc/20110412_act_en.pdf.
[5] K.H. Jansen, T.M. Brown, G.S. Samuelsen, Journal of Power Sources 195 (2010) 5409–5416.
[6] J. Taylor, A. Maitra, M. Alexander, D. Brooks, M. Duvall, IEEE Power & Energy Society General Meeting, 2009.
[7] O. van Vliet, A.S. Brouwerb, T. Kuramochib, M. van den Broekb, A. Faaij, Journal of Power Sources 196 (2011) 2298–2310.
[8] K. Clement-Nyns, E. Haesen, J. Driesen, IEEE Transactions on Power Systems 25 (2010) 371–380.
[9] S. Bashash, S.J. Moura, J.C. Forman, H.K. Fathy, Journal of Power Sources 196 (2011) 541–549.
[10] P. Kulshrestha, L. Wang, M.-Y. Chow, S. Lukic, IEEE Power & Energy Society General Meeting, 2009.
[11] N. Hartmann, E.D. Ozdemir, Journal of Power Sources 196 (2011) 2311–2318.
[12] T. Geist, H. Kamath, S.F. Porter, P. May-Ostendorp, Designing battery charger systems for improved energy efficiency, EPRI Solutions Report, 2006.
[13] J.C. Viera, M. Gonzalez, B.Y. Liaw, F.J. Ferrero, J.C. Alvarez, J.C. Campo, C. Blanco, Journal of Power Sources 171 (2007) 1040–1045.
[14] J. Weinert, J. Ogden, D. Sperling, A. Burke, Energy Policy 36 (2008) 2544–2555.
[15] R.A. Dougal, L. Gao, Z. Jiang, Journal of Power Sources 140 (2009) 409–415.
[16] Household Energy Price Index for Europe, E-control & Vaasa Ett Report, October 2010.
[17] AC propulsion. Ac-150 gen-2 ev power system. Integrated drive and charging for electric vehicles, www.acpropulsion.com.