Development of an Energy Management System for Minimizing Hydrogen Consumption in Fuel Cell and Ultracapacitor Hybrid Electric Garbage Trucks and Analysis of the Sizing Impact

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***Abstract*— The utilization of alternative energy sources in service vehicles, particularly in personal passenger cars, has been gaining prevalence in recent times. In this context, electric garbage trucks are becoming increasingly popular as an environmentally friendly alternative to traditional trucks. In this study, an optimization-based energy management system focused on minimizing hydrogen consumption is proposed for a fuel cell and ultracapacitor hybrid electric garbage truck. The specified energy management system takes into account the ramping rate constraints for the healthy operation of the fuel cell while ensuring that each source's natural structure is appropriately utilized for load sharing. Furthermore, the impact of fuel cell and ultracapacitor sizing on the energy management system's decisions is examined through various case analyses, and the effects of such sizing on hydrogen consumption and regenerative braking energy recovery are elucidated.**

Keywords*— *electric garbage truck; energy management; fuel cell; optimization; sizing; ultracapacitor.

Nomenclature

The relevant nomenclature for the developed approach is depicted in Tables I-III.

TABLE I. SETS

t	Set of time periods.

TABLE II. PARAMETERS

$a_{H\rightarrow P}$	Relationship coefficient between hydrogen quantity and power [kg/kWh].
CE	Ultracapacitor charging efficiency.
DRA_{FC}	Maximum allowed downward ramping amount per second for fuel cell power [kW].
DRA_{UC}	Maximum allowed downward ramping amount per second for ultracapacitor power [kW].
DE	Ultracapacitor discharge efficiency.
$ES_{UC-init}$	Initial energy state for the ultracapacitor at the starting moment [kWh].
ES_{UC-min}	Minimum allowed energy state for the ultracapacitor [kWh].
$Cap_{UC-energy}$	Ultracapacitor energy capacity [kWh].
$Cap_{UC-power}$	Ultracapacitor power capacity [kWh].
Cap_{FC}	Fuel cell power capacity [kW].
Cap_{HT}	Hydrogen tank capacity [kg].
$m_{H2-tank-init}$	Initial hydrogen amount in the hydrogen tank at the starting moment [kg].
$m_{H2-tank-min}$	Minimum allowed hydrogen amount in the hydrogen tank [kg].
$P_{load,t}$	Power demand of the electric garbage truck at time t [kW].
URA_{FC}	Maximum allowed upward ramping amount per second for fuel cell power [kW].
URA_{UC}	Maximum allowed upward ramping amount per second for ultracapacitor power [kW].
ΔT	Time resolution [h].

TABLE III. VARIABLES

$E_{braking-waste-tot}$	Total amount of unrecoverable braking energy [kWh].
$ES_{UC,t}$	Energy state of the ultracapacitor at time t [kWh].
$m_{H2-tank,t}$	Hydrogen amount in the hydrogen tank at time t [kg].
$m_{H2-cons,t}$	Hydrogen consumption by the fuel cell at time t [kg].
$P_{braking-waste,t}$	Unrecoverable portion of braking power value at time t [kW].
$P_{UC-dsch,t}$	Ultracapacitor discharge power value at time t [kW].
$P_{UC-ch,t}$	Ultracapacitor charging power value at time t [kW].
$P_{FC,t}$	Fuel cell power value at time t [kW].
u_t	Binary variable value at time t defined to prevent simultaneous charging/discharging operations of the ultracapacitor.

I. INTRODUCTION

A. General Introductory Information

The use of fossil fuels in transportation has significant environmental and economic impacts, leading to the search for alternative energy sources. While electric vehicles are gaining popularity as a clean and sustainable option, this trend is not limited to personal vehicles. Service vehicles such as garbage trucks have also become part of the electrification target [1]. For example, Volvo has developed the FE Electric garbage truck model, which has a battery capacity of 300 kWh and a range of approximately 300 km [2]. On the other hand, an electric garbage truck developed by BYD with a battery capacity of 178 kWh and a range of 130 km has started to be used in different countries worldwide [3]. Many more manufacturers have developed and launched different all-electric garbage truck models [4],[5]. However, using an all-battery structure in such vehicles, as mentioned in the world examples, poses challenges such as limited battery life and long charging times. In this context, applications that use alternative energy systems such as fuel cells and ultracapacitors together have the potential to emerge to increase applicability.

Meeting the power demand in related fuel cell and ultracapacitor garbage trucks according to the characteristic properties of the mentioned sources is important in terms of increasing the efficient use of resources. Fuel cells have relatively low power density and may be insufficient to meet instantaneous power demands. On the other hand, ultracapacitors have very high power densities and can be used to meet the mentioned instantaneous power demands and recover the braking energy that occurs during vehicle operation beneficially. In this context, it is of great importance to develop an effective energy management system structure for such service vehicles that will take into account the mentioned power density differences.

B. *Overview of the Existing Literature*

Although there is very limited literature on the energy management of electric garbage trucks, there is a broader literature on the energy management of electric service vehicles. When a classification is made in terms of related energy management approaches, applications based on different methods in control theory can be evaluated first. Among these, in the study conducted by Ferrara et al. [6], a model predictive control-based energy management system has been developed for a fuel cell and battery hybrid service vehicle, considering fuel consumption and the lifetimes of components. In the mentioned study, the power density situations of the fuel cell and battery have been taken into account, focusing on the efficient and longer-lasting use of the mentioned components. In the study given in [7] by a similar group of authors, a rule-based energy management system is proposed for fuel cell and battery hybrid electric service vehicles, and the effects of the mentioned energy management system on fuel consumption and component aging under real driving cycles have been examined. In the study mentioned in [8], conducted by the same research group, robust control theory has been applied to a fuel cell and battery hybrid service vehicle from this perspective, focusing on delaying aging to allow for longer component usage, particularly in terms of fuel consumption. In another study by the same group, an adaptive controller-based energy management system considering battery heating is proposed [9].

In a different study, Guo et al. [10] developed a dual deep Q-network-based energy management system for a fuel cell and battery-powered hybrid electric service vehicle. The approach developed in this study considers various operational factors, such as ensuring the fuel cell operates in its most efficient region, and has been comparatively analyzed with an intelligent energy management system, highlighting its advantages. Barelli et al. [11] developed a simultaneous perturbation stochastic approximation-based energy management system for a fuel cell and battery-powered hybrid electric service vehicle. The results of this study were compared with two other approaches based on fuzzy logic and genetic algorithms, examining the advantages of energy savings and maintaining an appropriate level of fuel cell power exchange.

Ravey et al. [12] conducted a study on direct fuel cell and battery-powered hybrid electric garbage trucks, proposing an approach for sizing hybrid system components within a fuzzy logic-based controller architecture, taking into account different driving cycles. Optimization-based energy management systems, on the other hand, are represented by fewer examples. In the study conducted by Ferrara et al. [13], a cost minimization-focused energy management system was applied, and a cost-effective sizing approach was developed, proposing a combined methodology. In a similar study with a real-time energy management system, Zendegan et al. [14] formulated the process of determining reference curves for resource power sharing in a fuel cell and battery-powered hybrid service vehicle as an optimization problem.

Comprehensive review studies examining various energy management system approaches for fuel cell hybrid vehicles, including service vehicles, are found in [15]-[17], recommended for examining common aspects of other studies in this field that cannot be listed here.

C. *Content, Contributions and Organization of the Study*

This study proposes an optimization-based energy management system for a fuel cell and ultracapacitor-powered hybrid electric garbage truck, aiming to minimize hydrogen consumption while considering the natural constraints brought about by the characteristics of each energy source. An in-depth analysis of component size-based sensitivity analyses is presented to evaluate the impact of fuel cell and ultracapacitor dimensions on hydrogen consumption and the amount of useful regenerative braking energy recovered.

The contributions of this study can be summarized in two aspects:

- The impact of fuel cell and ultracapacitor dimensions on the operation of a hybrid garbage truck under an optimization-based energy management approach has not been examined in the literature in this manner.
- A novel structure is presented, in which the natural power density characteristics of fuel cell and ultracapacitor units are considered as constraints for an optimization-based energy management system for service vehicles such as electric garbage trucks.

The remainder of the study is organized as follows: Section 2 presents the details of the mathematical model for the hydrogen consumption minimization-focused optimization-based energy management system developed for the fuel cell and ultracapacitor-powered hybrid electric garbage truck. In Section 3, simulation results, including comparative sensitivity analyses based on different fuel cell and ultracapacitor sizes, are presented. Finally, in Section 4, conclusions related to the study are discussed.

II. METHODOLOGY

The optimization model formulated for the operational energy management of a fuel cell and ultracapacitor hybrid electric garbage truck consists of Eqs. (1)-(19).

The objective function for the associated problem is given in Eq. (1). As can be seen, an energy management system structure aiming at minimizing consumption is established by minimizing the time-dependent total of the related hydrogen consumption according to the fuel cell power output.

$$\min Consumption = \sum_{t} m_{H2-cons,t} \quad (1)$$

The power balance within the electric garbage truck is given in Eq. (2). As observed, the fuel cell output power and ultracapacitor discharge power are used to meet the load demand. Moreover, the ultracapacitor can be charged by the fuel cell, and the braking power corresponding to the negative part of the load demand can be transferred as charge power to the ultracapacitor. A variable defining the value of the unrecoverable portion of the braking power at time t has been introduced to determine how much of the specified braking power remains unused in case the entire braking power cannot be stored by the ultracapacitor due to reasons like capacity constraints. Taking into account the time resolution of the related variable, the time-dependent total of its energy equivalent, as indicated in Eq. (3), gives the total amount of unrecoverable braking energy.

$$P_{FC,t} + P_{UC-dsch,t} = P_{load,t} + P_{UC-ch,t} + P_{braking-waste,t}\ ,\forall t \tag{2}$$

$$E_{braking-waste-tot} = \sum_t P_{braking-waste,t} \cdot \Delta T \tag{3}$$

The fuel cell, as indicated in (4), cannot provide power output beyond its capacity. The difference between the related fuel cell output power and the power value in the previous time interval is limited by the upward and downward ramping quantities shown in (5) and (6), respectively. The ramping-based constraint is considered to model the lower power density of the fuel cell compared to a high power density system like an ultracapacitor.

$$P_{FC,t} \le Cap_{FC} \forall t \tag{4}$$

$$P_{FC,t} - P_{FC,t-1} \le URA_{FC}, \forall t \tag{5}$$

$$P_{FC,t-1} - P_{FC,t} \le DRA_{FC},, \forall t \tag{6}$$

The hydrogen consumption requirement generated by the energy demand corresponding to the fuel cell output power mentioned above is calculated through (7), using the related conversion coefficient. Considering the specified consumption, the hydrogen quantity available in the hydrogen tank at each moment is determined as in (8). Here, the initial amount of hydrogen in the related hydrogen tank is defined by (9), while (10) ensures that the hydrogen quantity can only change between an allowed minimum limit and the hydrogen tank capacity.

$$m_{H2-cons,t} = P_{YH,t} \cdot a_{H\rightarrow P} \cdot \Delta T, \forall t \tag{7}$$

$$m_{H2-tank,t} = m_{H2-tank,t-1} - m_{H2-cons,t}, \forall t > 1 \tag{8}$$

$$m_{H2-tank,t} = m_{H2-tank-init}, if\ t = 1 \tag{9}$$

$$m_{H2-tank-min} \le m_{H2-tank,t} \le Cap_{HT}, \forall t \tag{10}$$

Both the simultaneous non-occurrence of the ultracapacitor unit's discharge and charge power and the constraint that the specified powers are lower than the ultracapacitor power capacity are ensured jointly by (11) and (12). The upward ramping limits for the ultracapacitor discharge and charge powers are constrained by (13) and (14), respectively, while the downward ramping limits for these powers are modeled through (15) and (16).

$$P_{UC-dsch,t} \le Cap_{UC-power} \cdot u_t, \forall t \tag{11}$$

$$P_{UC-ch,t} \le Cap_{UC-power} \cdot (1 - u_t), \forall t \tag{12}$$

$$P_{UC-dsch,t} - P_{UC-dsch,t-1} \le URA_{UC}, \forall t \tag{13}$$

$$P_{UC-ch,t} - P_{UC-ch,t-1} \le URA_{UC}, \forall t \tag{14}$$

$$P_{UC-dsch,t-1} - P_{UC-dsch,t} \le DRA_{UC}, \forall t \tag{15}$$

$$P_{UC-ch,t-1} - P_{UC-ch,t} \le DRA_{UC}, \forall t \tag{16}$$

Considering the aforementioned charge and discharge powers, along with charge and discharge efficiencies and time resolution, the ultracapacitor state of energy change equation, as indicated in Eq. (17), is derived. The initial value of the ultracapacitor state of energy at the starting moment is assigned by (18), while the permissible range of change for the related variable, determined between a minimum limit and the ultracapacitor energy capacity, is defined by (19). Lastly, for the final element of the time set, i.e., at the end of the evaluation period, the requirement that the ultracapacitor state of energy must be at least equal to the initial state of energy is ensured by (20). The reason for applying the related equation is that it is more reasonable in practice for the ultracapacitor to complete the current cycle in a certain state of energy that can meet the energy demand in a new possible driving cycle.

$$ES_{UC,t} = ES_{UC,t-1} + P_{UC-ch,t} \cdot CE \cdot \Delta T - \frac{P_{UC-dsch,t} \cdot \Delta T}{DE}, \forall t > 1 \tag{17}$$

$$ES_{UC,t} = ES_{UC-init}, if\ t = 1 \tag{18}$$

$$ES_{UC-min} \le ES_{UC,t} \le Cap_{UC-energy}, \forall t \tag{19}$$

$$ES_{UC,t} \ge ES_{UC-init}, if\ t = t_{final} \tag{20}$$

III. Test and Results

In the pertinent study, the Generic Algebraic Modeling System (GAMS) software and the commercially available CPLEX solver were employed to test the proposed optimization-based energy management approach for an electric garbage truck powered by fuel cell and ultracapacitor units.

A. Input Data

The power demand variation considered for the relevant electric garbage truck is depicted in Figure 1 [18]. For the specified power demand, the energy management system optimization problem was examined for different fuel cell power capacity and ultracapacitor energy capacity values. Here, the power capacity values considered for the fuel cell are 100, 150, 200, and 250 kW. The energy capacity values considered for the ultracapacitor are 10, 15, 20, 25, and 30 kWh. In light of the mentioned capacities, sensitivity analyses were conducted through 20 case studies, encompassing all combinations of the mentioned capacities, to examine the impact of the relevant capacity on both consumption and unrecoverable braking energy.

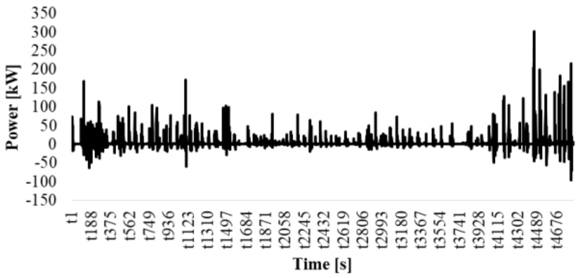

Fig. 1. Power demand variation of electric garbage truck.

The time resolution considered for solving the mentioned problem is 0.000277 h, corresponding to 1 second. The upward and downward ramping amounts for the fuel cell are set at 10% of the relevant power capacity. The conversion factor from hydrogen to electrical energy is 0.02985. The hydrogen tank capacity is 5 kg, with initial and minimum hydrogen amounts set at 2.5 and 0 kg, respectively. It can be noted that the mentioned hydrogen tank corresponds to a volume of approximately 200 liters, which gives an idea of its size [19]. For the ultracapacitor, the initial energy amount is set at half of the relevant capacity, while the downward and upward ramping amounts are determined to be ten times the relevant energy capacity. The minimum energy amount is considered to be zero. Finally, charge and discharge efficiencies for the ultracapacitor unit are set at 0.95.

B. Results and Discussion

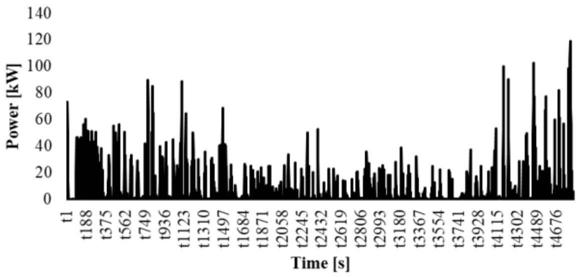

Fig. 2. Fuel cell power variation.

Firstly, the analysis results for the case corresponding to a combination of a 250 kW fuel cell and a 20 kWh ultracapacitor are graphically presented in Figures 2-7. Figure 2 shows the fuel cell output power. The fuel cell unit, which allows for the change in the related output power in accordance with the 25 kW downward and upward ramping amounts corresponding to the 250 kW fuel cell power, has effectively fulfilled its role as the primary source within the mentioned power change limits to meet the power demand of the specified electric garbage truck.

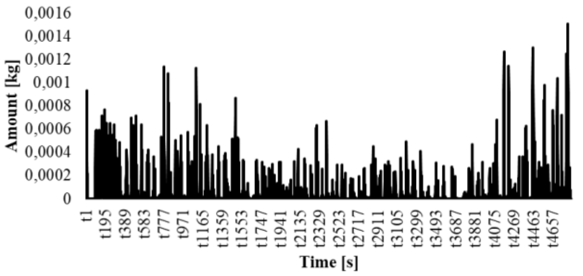

Fig. 3. Fuel cell hydrogen consumption variation.

The change in the amount of hydrogen consumed to meet the energy corresponding to the mentioned fuel cell power is shown in Figure 3. Along with the mentioned consumption change, the change in the total amount of hydrogen in the hydrogen tank is provided in Figure 4. By comparing the total hydrogen amount consumed in a short travel period to the maximum hydrogen amount stored in the hydrogen tank, it can be estimated that approximately 16 similar driving cycles can be performed with the mentioned consumption.

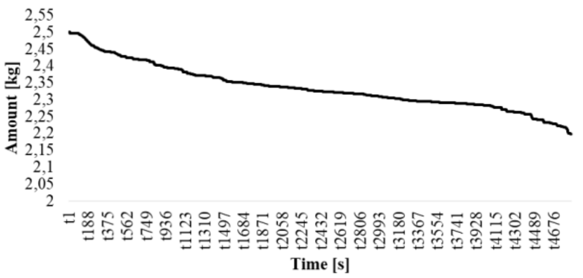

Fig. 4. The variation of total hydrogen amount in the tank.

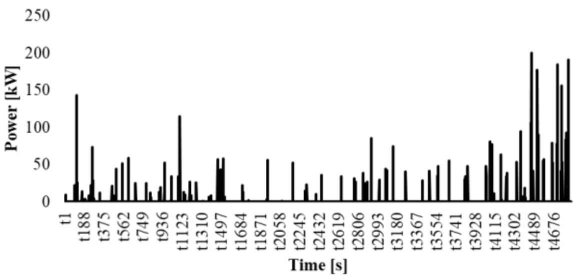

Fig. 5. Ultracapacitor discharge power variation.

The change in the discharge power of the ultracapacitor unit, which serves as a supplementary and high power density source in the system, is shown in Figure 5. As expected, the ultracapacitor unit has been used to meet faster power demands that are not reasonable for the fuel cell to handle in terms of its health and efficiency.

The change in the charge power of the ultracapacitor unit is depicted in Figure 6. As can be seen, the ultracapacitor unit has fully stored the braking power forming the negative parts of the power demand change given in Figure 1. Since a consumption minimization-focused optimization problem is designed, it should be noted that no significant charging of the ultracapacitor from the fuel cell occurs. However, more restrictive ramping amounts or different individual or combined objective functions may lead to more noticeable decisions in this regard within the energy management system.

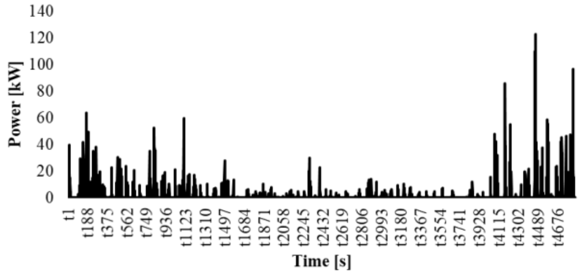

Fig. 6. Ultracapacitor charge power variation.

The change in the energy state of the ultracapacitor unit resulting from the charge and discharge processes indicated in Figures 5 and 6 is illustrated in Figure 7. With the mentioned energy state change, it can be observed that the energy state of the ultracapacitor at the end of the driving cycle is no lower than the initial state, making it available for possible subsequent driving operations.

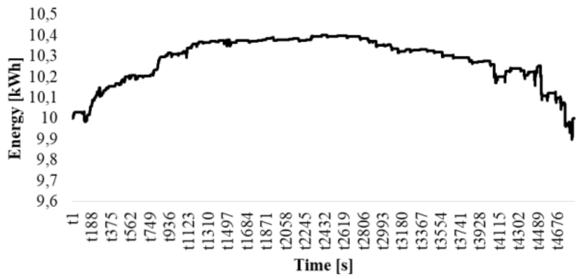

Fig. 7. Ultracapacitor state energy variation.

As seen in the results presented for a single combination of fuel cell and ultracapacitor dimensions, the proposed fuel cell and ultracapacitor-based hybrid energy source garbage truck effectively meets the power demand within the limits defined in the optimization problem. The impact of different fuel cell and ultracapacitor dimensions on hydrogen consumption and unrecovered braking energy amounts was analyzed under 20 different scenarios according to the dimension combinations, and the related findings are shared in Tables IV and V.

TABLE IV. CHANGE IN HYDROGEN CONSUMPTION AMOUNT IN KG WITH RESPECT TO FUEL CELL AND ULTRACAPACITOR CAPACITIES

		Ultracapacitor energy capacity [kWh]				
		10	**15**	**20**	**25**	**30**
Fuel cell power [kW]	**100**	-	-	-	0.30379	0.30378
	150	-	-	0.30377	0.30235	0.30216
	200	-	0.30289	0.30195	0.30191	0.30292
	250	0.30551	0.30213	0.30114	0.30072	0.30073

Firstly, it is noticeable that some capacity combinations in the mentioned tables do not provide results. In this case, when the maximum power amount corresponding to the fuel cell power capacity and the ultracapacitor energy capacity are combined, especially considering the stricter ramping limits for the fuel cell, the problem is concluded as infeasible. Particularly when examining the results corresponding to different ultracapacitor dimensions for a 250 kW fuel cell, it can be seen that as the ultracapacitor size increases, hydrogen consumption decreases by approximately 2%. It should be noted that the additional positive effect brought by the increase in fuel cell capacity remains at around 1%, and the increase in ultracapacitor size holds a more effective position. The difference between different fuel cell dimensions for the same ultracapacitor size is due to the fact that more flexible decisions can be made for the fuel cell as the power capacity and allowed ramping limits change. In this context, the direct effect of the increase in ultracapacitor capacity on the unrecovered braking energy amount is evident when examining the results presented in Table V. The decrease in the mentioned unrecovered energy amounts will indirectly affect the fuel cell hydrogen consumption when considering longer driving cycles.

TABLE V. CHANGE IN THE AMOUNT OF UNRECOVERABLE BRAKING ENERGY IN KWH WITH RESPECT TO FUEL CELL AND ULTRACAPACITOR CAPACITIES

		Ultracapacitor energy capacity [kWh]				
		10	**15**	**20**	**25**	**30**
Fuel cell power [kW]	**100**	-	-	-	0	0
	150	-	-	0	0	0
	200	-	0.01189	0	0	0
	250	0.10368	0.00910	0	0	0

It is especially worth mentioning that in none of the different scenario analyses presented here, the total simulation time exceeded 3 seconds on a workstation with an Intel(R) Xeon(R) CPU E3-1241 v3 @3.50GHz processor and 8 GB RAM.

IV. CONCLUSION

As interest in alternative energy sources grows due to the environmental and economic impacts of fossil fuels, electrification has become a target not only for popular electric vehicles but also for service vehicles such as garbage trucks. However, the use of purely battery-based systems can lead to issues such as long charging times and limited battery life. Therefore, applications that combine alternative energy systems, such as fuel cells and ultracapacitors, may be more suitable for service vehicles. Developing an effective energy management system structure is of great importance.

In this study, an optimization-based energy management system has been developed with the goal of minimizing hydrogen consumption, taking into account the natural characteristics of each energy source. Additionally, sensitivity analyses have been performed based on the component sizes, providing a detailed examination. It has been revealed that the size of the ultracapacitor, in comparison to the fuel cell size, has a greater impact on hydrogen consumption and the amount of useful regenerative braking energy recovered.

For future studies, it is recommended to develop a model predictive control-based real-time energy management system that takes into account the parametric uncertainty of the garbage truck's electrical load due to various reasons (such as changes in vehicle weight caused by the amount of collected garbage, etc.). Besides, the use of such a hybrid scheme in different applications will also be considered in future studies.

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