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Eng. Mikołaj Bartłomiejczyk, PhD.

Gdansk University of Technology

Faculty of Electrical and Control Engineering

Department of Electrical Transport

ul. G. Narutowicza 11/12

80-233 Gdansk, Poland

Phone +48 58 347 28 57

Email: mikolaj.bartlomiejczyk@pg.gda.pl

Marcin Polom, PhD.

University of Gdansk

Faculty of Oceanography and Geography

Department of Regional Development Geography

ul. J. Bazynskiego 4

80-952 Gdansk, Poland

Phone +48 58 523 65 69

Email: marcin.polom@ug.edu.pl

MULTIASPECT MEASUREMENT ANALYSIS OF BREAKING ENERGY RECOVERY

Abstract

Nowadays the issue of electric energy saving in public transport is becoming a key area of interest, which is connected both with a growth of environmental awareness in the society and an increase in the prices of fuel and electricity. That is why the reduction of energy consumption by increasing electrified urban transport, such as trams, trolleybuses, light rail and underground is becoming an increasingly important issue. Energy recovery during braking is possible in all modern electric vehicles, but in many cases this possibility is not fully taken advantage of, inter alia, because of an inadequate power supply structure. The aim of this article is to present practical examples of implementation of eco-friendly solutions in urban municipal transport. The article shows a thorough analysis of braking energy dispatch in the urban traction power supply system, which was based on extensive measurement research conducted in Gdynia trolleybus network. The authors applied multi way measurement method using Global Positioning System. The optimal conditions for implementation of several methods of energy recovery (storage energy systems, reconfiguration of supply system, using auxiliaries) have been shown. Great emphasis has been put on the confirmation of the results by means of research and experimental measurement.

Keywords

Trolleybus, energy recuperations, public transport, supercondensators, energy consumption reducing

1. Introduction

The development of zero-emissions public transport vehicles is one of the EU's horizontal policies. Urban transport currently accounts for 40% [1] of total CO_2 emissions generated by road traffic in Europe. The transport sector is responsible for 30% of total energy consumption and 27% of greenhouse gas emissions. Among all sectors that emit CO_2, the transport sector is the fastest growing one, second only to the industrial sector [2]. Therefore, by 2050, greenhouse gas emissions will have to be reduced by 60%. In addition, the instability of liquid fuel prices has a strongly negative effect on the economy [3]. It thus becomes imperative to raise the level of the usability of alternative energy sources in public transport [4]. Analysis of the impact of transport on the environment and of ways of reducing its harmfulness has been the subject of numerous analyses. Studies for Tianjin (China) [5] or Delhi (India) [6] can be an example here. Article [5] highlights the impact of the development of the city on the increase of communication needs in the years 2010 - 2040 as well as the risks it could bring. If there will be no changes in next 30 years, the number of vehicles will grow more than 7 times and energy consumption will rise up to 6 times. The similar increase of transport energy demand (6 times in years 1997 - 2020) is estimated for Delhi and Mumbai [6].

Electricity seems a natural alternative to liquid fuels. For this reason, European authorities actively support the development of electrically-powered means of transport, as manifested by co-funding initiatives promoting environmentally-friendly city transport systems. For example, the *Trolley* project implemented in the years 2010-13 was aimed at promoting trolleybuses and developing energy-saving technologies in these vehicles. A project similar in scope was *Actuate*, whose objective is to accentuate the importance of driving technique for the energy efficiency of electrically-powered transport modes and to implement the concept of "eco-driving", i.e. eco-friendly driving technique. At present, many European cities support the *Dyn@mo* programme, the purpose of which is to develop modern and energy-efficient technologies in urban transport. A programme focusing exclusively on the technical aspect of tramway transport energy-efficiency is *Osiris*. The programme participants include a team of transport companies and manufacturers of broadly-defined electrical equipment [7].

Over the last quarter-century there have been many efforts and projects undertaken related to the reduction of global energy consumption, as well as increasing the efficiency of its generation and transmission [8]. Decreasing energy consumption in transport plays an important role in this issue [9]. Electric vehicles can be one of the key elements in curbing CO2 emissions [10] and they can be an active part of the energy system contributing to the improvement of its work and reliability [11]. An important issue related to the public transport energy consumption is the impact of traffic conditions and the structure of the power supply system on energy consumption and energy balance [12]. In the energy balance of the modern transport system a vital role is played by recuperation of braking energy, which can be an effective tool to reduce energy consumption [13]. Supercapacitor storage energy systems are the most popular tool for enhancing the recuperation usage [15].

In classical DC supply systems of public transport (tramways, trolleybuses) recovered energy can be re-used by auxiliary receivers in breaking vehicle or by other vehicles [15]. In case of lack of vehicles which are accelerating at the same time, this energy is burned in breaking resistors. In order to avoid the loss of recuperated energy the storage energy systems can be used [14]. The importance of optimization of storage devices for regenerative breaking energy is becoming a significant issue [8]. In previous years flywheels were considered to be an optimal solution [16], but nowadays supercapacitors are the most popular device used for recovery energy accumulation [17]. They are the subject of numerous scientific research projects, both in the on-board form, placed in the vehicles and off board energy storage devices situated in traction substations or off-board form in stationary places of supply systems [1]. Publications are mainly focused on control algorithms [18]. There are two main objects of research in literature as far as increasing energy efficiency is concerned: on board energy storage devices for light electrical vehicles (LEV) like trams, trolleybuses and electro buses [11] or reducing the energy consumption in heavy electrical vehicles (HEV, railway, suburban railway, metro) [13]. In contrast to this, the lack of research in the field of off board storage energy systems for LEV is visible. The tram and trolleybus transport is highly developed in many European cities, a lot of tram and trolleybuses operators are considering putting into service off board energy storage systems. In metro systems savings caused by using storage energy systems can reach 44% [19], moreover the character of traffic in case of LEV differs significantly from HEV and a special approach for energy consumption analysis is required. The savings caused by storage energy systems can be much lower due to different shape of speed profiles and the larger number of vehicles in motion [20].

In addition to the above, another deficiency of the present science research can be mentioned: there are a lot of publications available related to the problems of design and management of the recuperated storage energy systems [21]. However, they are oriented only on re-using the recovered energy in storage systems. Studies on the global energy flow are very rare. Nevertheless, the global system approach is a crucial element for energy analysis of supply systems [22]. Very interesting analysis of the global energy supply tram system is presented in the paper [23], however, its experimental verification was not carried out. Several ways of implementing eco-friendly technologies with assessment of benefits were presented in [24]. In [25] the importance of recovery of breaking energy was presented, which was described as the cheapest way of reducing energy demand.

In order to make up for the gap in literature, this paper presents a comprehensive overview of the options of re-usage of energy breaking in urban transport system. Firstly, the aim of the authors is to present the importance of a multifaceted approach to the multi way use of energy on the real case-study of Gdynia trolleybus system. In this aspect, the results of the research presented in this article refer to the works [24] and [25]. Secondly, great emphasis has been put on the confirmation of the results by means of research and experimental measurement. Many similar analyses are based on simulation models of power supply systems [26]. Nevertheless, in the view of a considerable number of factors affecting urban tram of trolleybus traffic, mainly congestion with its random and unpredictable nature, psychological aspects of drivers work and low repeatability of measurements [22], careful analysis of the supply system using a theoretical simulation does not involve many factors and is associated with inaccurate results. Thirdly, the authors present the novel method based on the multi way measuring, realized both in traction substations and vehicles with GPS synchronization. Due to the limited measurement possibilities, a lot of analyses of power supply systems are based only on measurements made in traction substations [27] or in vehicles (tramways [26] or trolleybuses [28]).The method presented in this paper is based on global approach to the supply system.

The aim of this paper is to present the activities applied in Gdynia Trolleybus company, which may be "ready to use" solutions for other transport companies. The article highlights the impact of practical verification of energy reduction tools in electrified transport. The novel multi way measurement method using GPS localization system was applied for this purpose. Moreover, the "niche" ways of increasing efficiency, f.g. "intelligent heating" are described in the article.

2. Trolleybus transport system of Gdynia

Gdynia is a harbour city at the Baltic sea with a population of 250,000. In 1943, its trolleybus network was put into operation and gradually developed, later to become the largest in Poland. Gdynia's trolleybus carrier, Przedsiębiorstwo Komunikacji Trolejbusowej (PKT), currently operates a fleet of 85 trolleybuses on 12 services in a network, the length of which reaches almost 50 km. Gdynia's trolleybus network is powered from 10 traction substations in a unidirectional supply system. The traction substations differ with respect to the size of areas to which electricity is supplied and the number of rectifier sets, each substation powering 1 to 6 sections. Gdynia's trolleybus system consumes nearly 12 GWh of electrical energy per year and is considered one of the biggest energy consumers in the city.

Therefore, one may reasonably expect that some steps towards reducing power consumption would be appropriate [21].

Since 2001, PKT Gdynia has been involved in many activities related to the reduction of power consumption, both in terms of implementation and research and development. The former category includes putting vehicles with an energy-efficient drive into operation and the installation of supercapacitor energy storage in one of the traction substations, the latter - studies on the potential for a further limitation of energy consumption and methods to achieve it. PKT Gdynia participates in two research and development programmes: *Trolley* and *Dyn@mo*, in addition to cooperating with Gdańsk University of Technology.

The fleet modernization programme started in 1998 and caused a significant drop in the power consumption for the PKT company: for the last 10 years the average annual consumption has been reduced from 2.7 kWh/km to 2.1 kWh/km, which corresponds to a 22% decrease of energy consumption by trolleybus transport. The graph in Fig. 1 illustrates changes in the relative number of vehicles with power electronics drive and the corresponding average annual energy consumption. An increase in the number of vehicles with modern propulsions system allowed to significantly reduce the consumption of energy. In order to further reduce energy consumption the company started cooperation with Gdańsk University of Technology which provides numerous research studies related to the broadly-defined improvement in the efficiency of energy recovery.

The issues of reduce energy consumption in Gdynia have been the subject of many scientists works and as well as analysis of the author. Some of them have theoretical character. In [29] the novel method of trolleybus supply system analysis by statistical method Monte Carlo was presented. The method was used in order to present the possibility of reducing energy consumption by using new technologies, mainly by implementation of bilateral supply system and storage energy devices. The several novel tools for urban supply system such Multi Criteria Decision Analysis or statistical analysis of load probability were presented in [30]. Some of practical experiences gained during exploitation of the thirst, trail storage energy system were presented in [31]. This is the first study, which presents results of all activites focused on the reduction of energy consumption conducted in Gdynia for a wide range. Beside these it gives a general overlook of practical application of eco friendly technologies in public transport.

3. An overlook of recuperation of braking energy

Every electrical machine is characterized by its capability of operating with a bidirectional energy flow [32]. For traction motors it means that braking enables regenerative operation which consists in converting the vehicle's kinetic energy into electrical energy, which in turn generates braking torque. This allows to recuperate energy. During the start up the traction motor propels the vehicle, thereby increasing its velocity. Thus, the electric energy supplied to the drive system is converted into kinetic energy of the vehicle. During braking, the vehicle speed is decreased, which leads to a reduction of its kinetic energy. This energy can be dissipated, for example in the brake pads. Yet it is also possible to transform it again into electric energy by means of an electric motor. In real conditions it is possible to recover 40% of energy consumed for acceleration [29].

Fig. 2 presents a diagram of the energy flow in a vehicle during the braking of an electric traction unit. During braking, the traction motor (TM) switches into a generator mode and a transformation of the kinetic energy of the vehicle into electrical energy takes place, which can then be returned to the overhead lines. However, in order to return electric energy into the supply system it is necessary to generate voltage higher than the one in the overhead lines. For this purpose, during braking, the traction inverter (TC) increases the voltage generated by the traction motor. First, part of the generated energy is consumed in the vehicle by auxiliary needs (mainly heating). The rest of the recuperated energy is directed through the braking converter (BC) into the overhead lines. In the absence of reception of the braking energy, voltage in the overhead lines (U_{CN}) on the vehicle's current collector exceeds the maximum recuperation voltage U_{max}. This triggers the braking converter BC, which directs the energy generated in the drive unit to the braking resistor. This energy is dissipated as heat.

An example of the balance of energy recovery is shown in Fig. 3. It presents energy balance in supply areas of traction substations in Gdynia. The diagram presents energy consumed from the supply system for traction purposes, total energy recovered from braking and energy dissipated in braking resistors. The differentiation of recovered energy load is visible. In the majority of supply areas almost all energy generated during braking is consumed, but in areas of substations no. 4, 9, 10 a significant part of braking energy is dissipated, and in case of substation no. 10 almost all braking energy is lost. It shows the possibility of reducing energy consumption and proves the need to analyze braking energy usage.

Effectiveness of energy recovery depends on the structure and topology of traction supply system. An overhead catenary is divided into supply sections to which electrical power is delivered from traction substations. In a conventional supply system, in which substations are not equipped in power storage accumulators, the recovered energy may be absorbed by another vehicle which is in motion and located in a power supply section capable of receiving power. Yet frequently in the supply area there are no vehicles capable of absorbing power. In such cases the recovered energy is wasted on the braking resistors. This results in only partial use of the system's regenerative potential [29].

One of the methods of preventing energy losses in braking resistors is to direct the recovered energy to public AC network which supplies power to traction substations equipped with inverters and feed it back to the power supply network. However, this method is not popular due to insufficient interest of electrical energy suppliers in purchasing the recovered recuperation energy.

An alternative solution is to store the recovered energy in supercapacity energy storage systems to reuse it to power moving vehicles in the future. The means of storing the recovered energy may be located in vehicles (on-board energy storage systems) or in tractions substations or in other places of supply network (off board energy storage systems). Fig. 4. shows the distribution of the recovered energy in a trolleybus supply system, in which energy storage is installed in a traction substation. Part of the recovered energy $E_{recuperation}$ generated during regenerative braking is used to satisfy internal demand of the trolleybus (lighting, auxiliary drives, heating etc.) – and is marked as $E_{auxiliary}$. The remainder of the recovered energy is fed back to the contact system, in which it is partly absorbed by other vehicles in the supply area ($E_{network}$), with the remainder ($E_{storage}$) stored in an energy storage facility.

Recuperation energy balance may be described by the following equation:

$$E_{recuperation} = E_{auxiliary} + E_{network} + E_{storage} \quad (1)$$

The values of particular recuperation energy balance elements are dependent on parameters such as the type of fleet in use, traffic intensity, power supply system structure, amount of consumption needs of nontraction vehicles.

The relation between particular recuperation components may thus change. As a result, the use of solutions that increase the efficiency of recovery should be subject to the space-traffic conditions of the transport system. It allows to propose the following thesis: for the sake of energy recovery optimization of all components of the energy recuperation balance should be included, their distribution depending on many factors, predominantly the topology of the power supply system. Efficient use of recovery energy is possible only basing on the synergy of methods increasing the use of recuperation energy. The potential for increasing the re usage of the recovered energy, on the example of Gdynia trolleybus system, is shown in Fig. 3

which presents measurement results of traction energy balance. Possibilities of increasing of the breaking energy recovery are clearly visible, mainly in supply area of substations 4, 9, 10.

4. Methods

Gdynia's supply system was tested in this respect in the years 2011-2015. Measurements were performed in traction substations and on trolleybuses. For this purpose an on-board energy consumption logging system providing information on the vehicle's GPS location at a given point in time was used [33]. Vehicles in service in Gdynia are fitted with the system as a standard. The functionality enables precise energy consumption read-outs in individual supply sections.

The following values were established during measurements in order to determine energy recovery effectiveness indicators:

- in traction substations:
    - power supply units' voltage and current,
    - busbar voltages,
- in vehicles:
    - traction drive voltage,
    - auxiliary equipment voltage and current,
    - braking resistor activation time,
    - current collector voltage.

The results were based on read-outs taken from December 2011 to November 2012, with the winter period defined as January and February, and the summer period defined as July and August. The scheme of the measurement is shown on Fig. 5

4.1. Recuperation for auxiliary needs

The non-traction need plays a significant role in global energy consumption of transport vehicles [34]. Therefore, the most efficient way to use energy recovery is its consumption inside the vehicle, to non-traction needs. The main non-traction recipients of energy is heating and air conditioning, whose work is highly dependent on weather conditions. Thus, the value of energy used for non-traction purposes is strongly dependent on the season and weather conditions. This is also reflected in the amount of recuperation energy consumed for non-traction purposes. Fig. 6 shows the relative amount *k* of recuperation energy consumed by non-traction needs in the vehicles needs (related to total energy consumption of the whole trolleybus transport system) in one year scale from January to December. During the winter season even more than 30% of recuperated energy can be used for non-traction purposes.

Recuperative energy consumption for the vehicles' non traction purposes is the most effective form of energy recovery use, thus the on-board equipment should be constructed in such a way that it is primarily supplied with recuperation energy. This can be achieved by e.g. introducing intelligent heating: the power of heaters is raised during regenerative braking and reduced while driving, which allows for an increase in the share of recuperation energy in heating the vehicle. This solution was implemented in Gdynia in two vehicles. The process control system is as follows: during normal driving the temperature of heating liquid in the heating system is kept at the level of 60° – 70° Celsius by hysteresis controller. When braking occurs, the power of heating units is increasing to its maximal value, thus necessitating greater use of recuperation energy for heating needs. Fig. 7 shows the difference between the recovered energy consumption for auxiliary needs in a vehicle with the standard heating system and the intelligent heating system. In the intelligent heating system the usage of the recovered energy for auxiliaries is even twice as high.

4.2. Recuperation for other vehicles

In order to recover braking energy it is necessary to ensure the receivers for the generated energy. In a classical supply system without storage energy systems, with one-side supply of catenary and without taking into account transmission losses, this means that substation load P_{TS} must be larger than power P_{rec} generated during recuperation by vehicles in the supply area of the substation. It can be written as the equation:

$$P_{TS} \geq P_{rec} \tag{2}$$

If this condition is not fulfilled, only a part of recuperated power, equal to load P_{TS}, can be re-used. The remaining energy is lost in braking resistors. Therefore, due to limited load power P_{TS} of substation, it is possible to use only a part of the generated energy.

The influence of changeable substation load P_{TS} on the possibility of absorption of generated power has been examined [30]. It has been analyzed how much energy from the source with power P_{gen} the supply system with changeable value of load P_{TS} (t) is able to absorb. Source P_{gen} is an equivalent of vehicle during regenerative braking. The calculations were based on registrations of loads P_{TS} (t) of traction substations in Gdynia.

For this purpose, function $e(P_{gen})$, which expresses the relative amount of generated energy from source P_{gen} in time T, has been defined:

$$e(P_{gen}) = \frac{\int_0^T P_{Ch}(P_{gen}, t)\,dt}{P_{gen} \cdot T} \tag{3}$$

$P_{Ch}(P_{gen}, t)$ expresses the limit of absorption of generated energy:

$$P_{Ch} = \begin{cases} P_{gen} < P_{TS} \rightarrow P_{Ch} = P_{gen} \\ P_{gen} \geq P_{TS} \rightarrow P_{Ch} = P_{TS} \end{cases} \tag{4}$$

In Fig. 8 the values of relative usage of generated energy are presented. Characteristics of two substations: TS 2 and TS 9, are shown. These two substations are significantly different in terms of traffic intensity. TS 2 supplies large supply area with high density of traffic (every 3 minutes), whereas TS 9 supplies the sub-urban line with a minor traffic intensity (30 minutes). The difference in the traffic intensity is reflected in the possibility of using regenerative braking. Assuming regenerative braking power level at 100 - 200 kW, it can be noticed that in case of TS 2 substation 80 - 90% of energy generated during the recuperation can be absorbed by the supply system. In case of TS 9 substation the level of recuperation usage is only 20 - 30%.

The dependence between density of trolleybus traffic and possibility of generated energy absorption is reflected in characteristic of recuperation effectiveness. In Fig. 9 the value of recuperation effectiveness in function of an average number of vehicles in the supply area of the substation is presented. Effectiveness of recuperation is defined as the rate between the recovered braking energy and the energy consumed by traction drives. Greater number of vehicles in one supply area means higher probability of absorption of the recovered energy. As a result, the recuperation effectiveness increases with the number of vehicles in the supply area. In case of high density of traffic (more than 10 vehicles running) it is possible to recover around 40% of consumed energy, which is very close to the value of recuperation potential estimated in the beginning of this paper.

4.3. Energy storage systems

If the generated power is not received, it may be stored in a tray storage system for later use. The supercapacitors storage system are the most popular technology of energy storage. In 2009 the PKT began to cooperate with the Traction Department of the Institute of Electronics in Warsaw (IEL) to launch in-service tests of a supercapacitor storage device installed in a traction substation in Gdynia. The device was designed to accumulate energy from regenerative braking. Gdynia storage device was installed in April 2011 in *Północna* trolleybus traction substation. *Północna* is a two-set traction substation which had undergone a complete modernisation in August 2010. The substation is fitted with two sets of rectifiers with a transformer rating of 1200 kVA each and powers 6 supply units. Currently it is the largest traction substation in Gdynia trolleybus network. The electrical capacitance of installed supercapacitor modules is 0.7 kWh.

Positive exploitation experience of the energy supercapacitor installed in *Północna* substation gave grounds for the decision to install another supercaps tank, which was located in Wielkopolska traction substation. It is a small substation equipped with one rectifier unit of 1200 kV, supplying only one catenary power supply section. It feeds the trolleybus network in a hilly area of Gdynia, where the value of the road gradient reaches 8%. It is the cause of a substantial recovery braking energy generation, which predetermined a supercapacitor installation in this substation.

The supercaps tank was launched in 2014. Its energy capacity is 1.5 kWh and it consists of two parts: the converter block is located inside the substation building, whereas the supercondenser modules are placed in the outside container. Fig. 10 shows a comparison of the relative value of energy recovery in vehicles equipped with a regenerative braking system before and after the installation of the supercapacitor energy storage system.

Fig. 11 shows the relation between the average number N of the vehicles, which express the density of trolleybus movement on the individual supply sections and the value of recuperated energy consumed by other vehicles $E_{network}$ and recuperated energy stored in supercapacity bank $E_{storage}$ referred to value of energy recuperated by propulsion $E_{recovery}$. At weekdays when trolleybus traffic intensity, which is expressed by the average number of trolleybuses on the power supply area, is at the level of two vehicles, 70% of the recovered energy is absorbed by other vehicles in traffic, and only 20% of this energy is stored in the tank. Thus, the reduction of energy consumption associated with the work of the supercapacitor is as low as 10%. In contrast, during days off work, when the frequency of trolleybus runs is decreased by a half and there is an average of one vehicle on the power supply section, the exploitation of a supercapacitor rises significantly since it accumulates from 50% to 70% of recovered energy. Another issue worth noticing is a variation on an annual basis, which is associated with a variable value of energy consumption for non-traction vehicles needs [9].

5. Discussions

There are three ways to re-use the recovered energy: consumption by auxiliaries in the vehicle, consumption by other vehicles and storing energy in storage systems. In the performed analysis the importance of all these three ways was shown.

Recuperative energy consumption for the vehicles non-traction purposes is the most effective form of energy recovery use, thus the on-board equipment should be constructed in such a way that it is firstly supplied with recuperation energy. This can be achieved by e.g. introducing power modulation of heating units; the power of heaters can be raised during regenerative braking and reduced while driving, which will allow for an increase in the share of recuperation energy in heating the vehicle. As it is presented in Fig. 7, in case of intelligent power modulation of heating unit during winter season it is possible to consume most of the recuperated energy. It allows to significantly reduce the load of supply system and reduce the transmission losses.

Utilization of the recuperated energy inside vehicles plays an important role in reducing the energy consumption. Nevertheless, even in winter season there is no possibility to consume all recuperated energy by auxiliaries. Furthermore, in spring or autumn season the use of the recuperated energy by auxiliaries drops to 20-30% (Fig. 6), therefore it is necessary to return back the recuperated energy to DC supply system, which was the second tested element of the energy balance. As research has shown in a classic supply system (without supercapacitors) it is possible to use most of recuperation energy by vehicles in motion (Fig.

11). In the case of high traffic density, the level of recuperation efficiency reaches 40%, which is the maximal possible technical level of breaking energy recuperation. It can be concluded, that almost all generated energy can be consumed on the way vehicle - a vehicle. This is important especially in the realities of Central Europe, where the central power systems with large traction substations and extensive areas of power are predominant. The failure of energy usage occurs in case of energy supply areas with low traffic intensity. Therefore, solutions facilitating the flow of recuperation energy between vehicles and extending galvanically connected traction network areas should be applied. It can be achieved by, for example, introducing a bilateral power supply system. It can be concluded that dense division of a supply system into small, galvanically isolated supply areas is not recommended, because it impedes an exchange of the recovered energy between the vehicles. Therefore, designing a supply system facilitating the flow of recovered energy should be treated as a priority. Creating the largest possible areas of a galvanically connected contact system is also highly recommended. Supply areas should be enlarged by connecting together areas of neighboring substations by bi-directional supply of the contact network. This will allow the flow of recovered energy between supply areas of different substations. Moreover, in order to facilitate energy flow between the supply sections, the neighboring sections can be joined. Voltage losses in the DC supply system limit the flow of the recovered energy. The efficiency of recuperation and recovered energy transfer can be improved by the reduction of no-load voltage of the substation. Lowering the no-load voltage by 20 V brings a decrease of energy consumption of 3% [35].

In case of small traction substation supplying only one or two supply sections at the same time only one or two vehicles occur in the supply section. This low number of vehicles makes it difficult to exchange recovered energy between vehicles and the efficiency of energy recuperation drops under 20%, what is seen in case of TS9 and T10 in Fig. 3 and 8. Therefore application of the supercapacitor is most efficient at low intensity traffic or in a hilly area. Supercapacitors ought to be used as complementary to the power system where generation of recuperation energy is significant or where reconfiguration of the network power supply system is not viable. The effectiveness of SC storage system operation is also high at low intensity traffic. However, in this case the total amount of energy saved in the tray is small, because despite the high relative value of the reduction of energy consumption installation of SC storage system may be unprofitable.

We should also emphasize the practical importance of the method of estimating the potential recovery, which was presented in chapter 4.2, (2) - (4) . It is possible to yield measurement data to assess the current utilization of recuperation easily (Fig. 8).

6. Conclusions

Table 1 presents comparisons of the discussed methods. Unused energy is the cheapest form of energy. Recuperation of braking energy allows to reduce the energy losses in braking resistors. As a result, total energy consumption decreases. In the paper the authors have shown practical aspects of increasing of breaking energy recovery in public transport.

The main novelty of the presented method is a combination of measurements of the geographic parameters (GPS) with electrical ones (voltage and current of drive system). This allows the energy consumption analysis in terms of geography characteristic. Thanks to this factors that affect the energy consumption at the local level are taken into account.

The aim of the conducted study was to present the results of experiences of PKT Gdynia in the field of energy consumption reduction. The solutions applied in Gdynia may be “ready to use” solutions for other transport companies. Moreover, the article highlights the impact practical verification of energy reduction methods in electrified transport. Analysis which are based on real measurements are more reliable for practical applications than theoretical simulation and analysis. This presented measurement methods perfectly complement the existing theoretical state of art. As the result, the practical impact of the article increases and presented results of the research can be applied in wider range.

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Provides:

Figure. **1.** Graph of changes the relative share of the number of vehicles driven power electronics k and the average consumed energy *E* on a scale of years 2002-2013.

Figure. 2. Braking energy low flow in vehicle, U_{CN} – voltage of contact supply network**,** E_k kinetic energy of vehicle, TM – traction motor, TC – traction controller, BC – braking controller, RH – braking resistor

Figure. 3. Energy consumption for traction needs, energy recovery and energy dissipated (lost) in braking resistors in several supply areas of traction substations in Gdynia

Figure. 4. The load flow of the recovered energy by traction propulsion, which can be consumed by auxiliary needs, other vehicles running in network or can be store in supercapacitor energy bank.

Figure. 5. The scheme of measurement system, the points of measurements are shown: (1) supply section load, (2) storage energy bank load, (3) vehicles load. GPS coordination allows to analyze load of vehicles in particular supply section.

Figure. **6.** Relative amount *k* of recuperation energy consumed by non traction needs in the vehicles needs (related to total energy consumption in scale of all trolleybus transport system) in one year scale from January to December. The average one-day values are shown.

Figure. 7. The difference between recovered energy consumption for auxiliary needs in a vehicle with the standard heating system and the intelligent heating system

Figure. 8. Relative usage of recuperated energy in function of value of recuperation power for two substations: TS 2 and TS 9.

Figure. 9. Recuperation effectiveness in function of average number of vehicles in the supply area of the substation.

Figure. 10. shows a comparison of the relative value of energy recovery in vehicles equipped with a regenerative braking system before and after the installation of the supercapacitor energy storage system.

Figure. **11.** Relation between the average number *N* of the vehicles, which express the density of trolleybus movement on the individual supply sections and the value of recuperated energy consumed by other vehicles $E_{network}$ and recuperated energy stored in supercapacity bank $E_{storage}$ referred to value of energy recuperated by propulsion $E_{recovery}$

Table 1. Comparison of methods of increasing the efficiency of recuperation

Table(s)

Table 1. Comparison of methods of increasing the efficiency of recuperation

Use of recuperation energy	*Method of increasing recuperation*	*Energy savings*
Recovered energy consumption in a vehicle	Implementation of an "intelligent" heating	3 - 10%
Transfer of recovered energy between vehicles	Implementation of bilateral supply of traction network	5 - 15%
	Splitting the neighboring supply sections	1 - 5%
	Reducing of no-load substation voltage	1 - 5%
Accumulation of recovered energy	Use of the energy storage systems	5 - 30%

Figure 1

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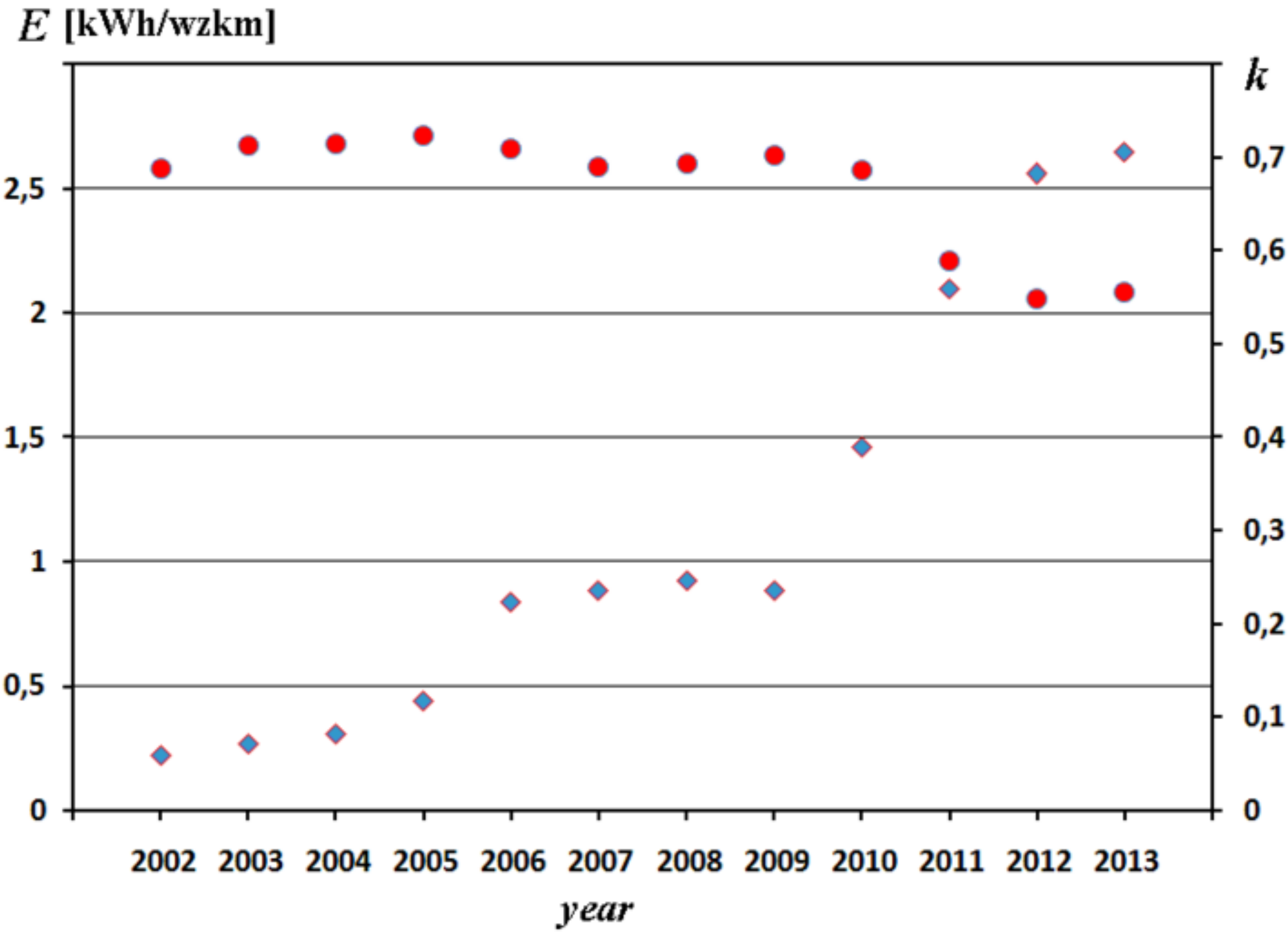

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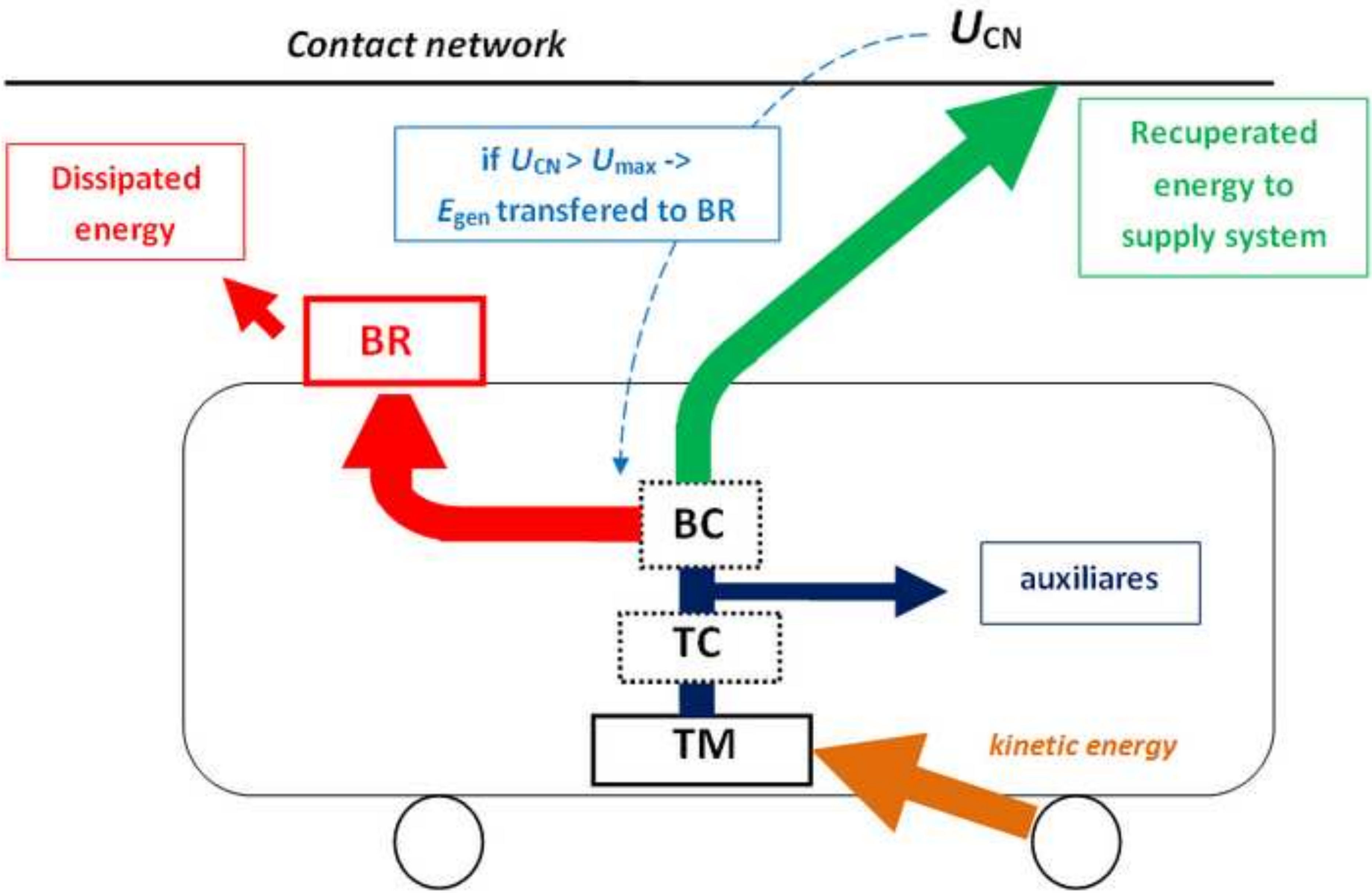

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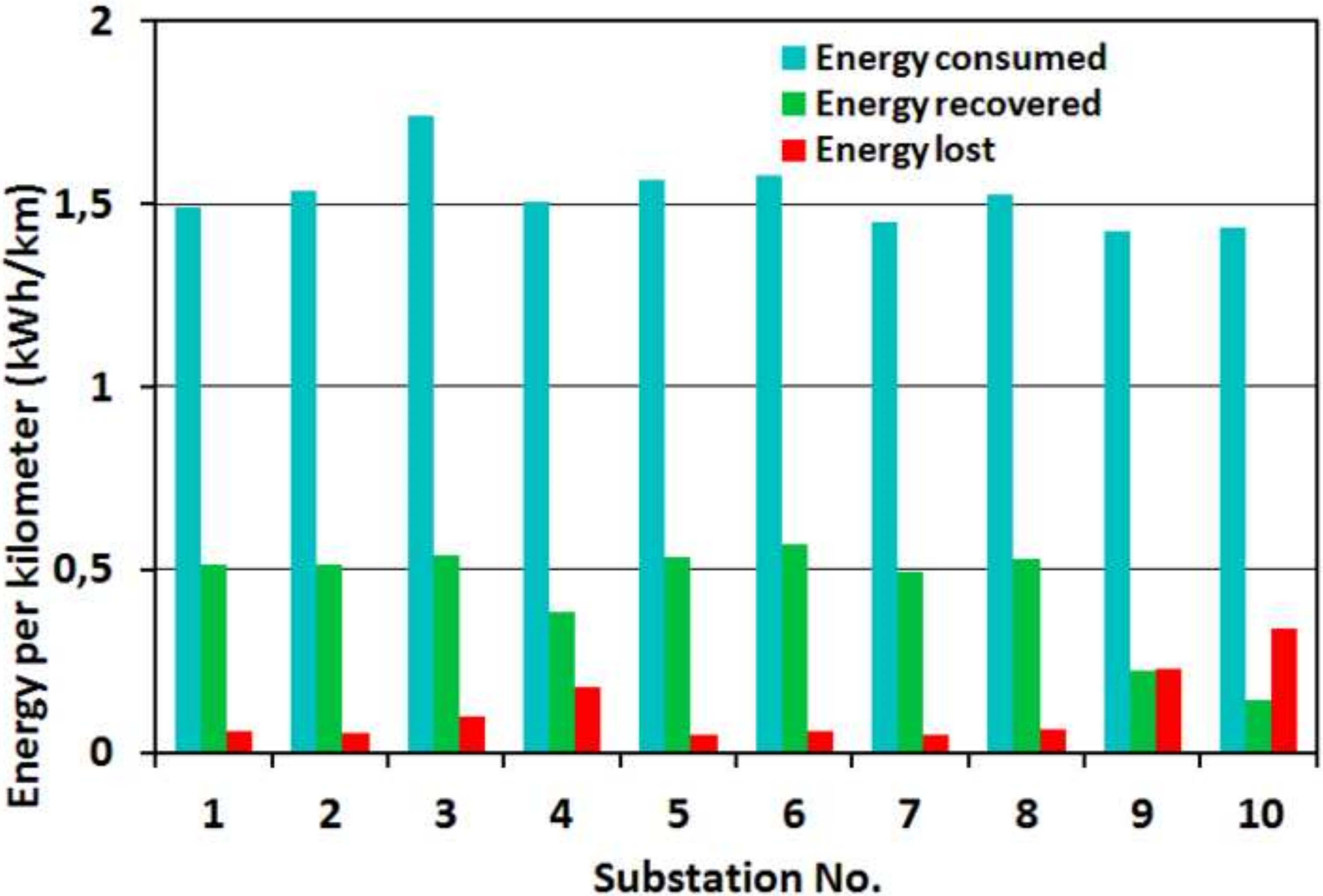

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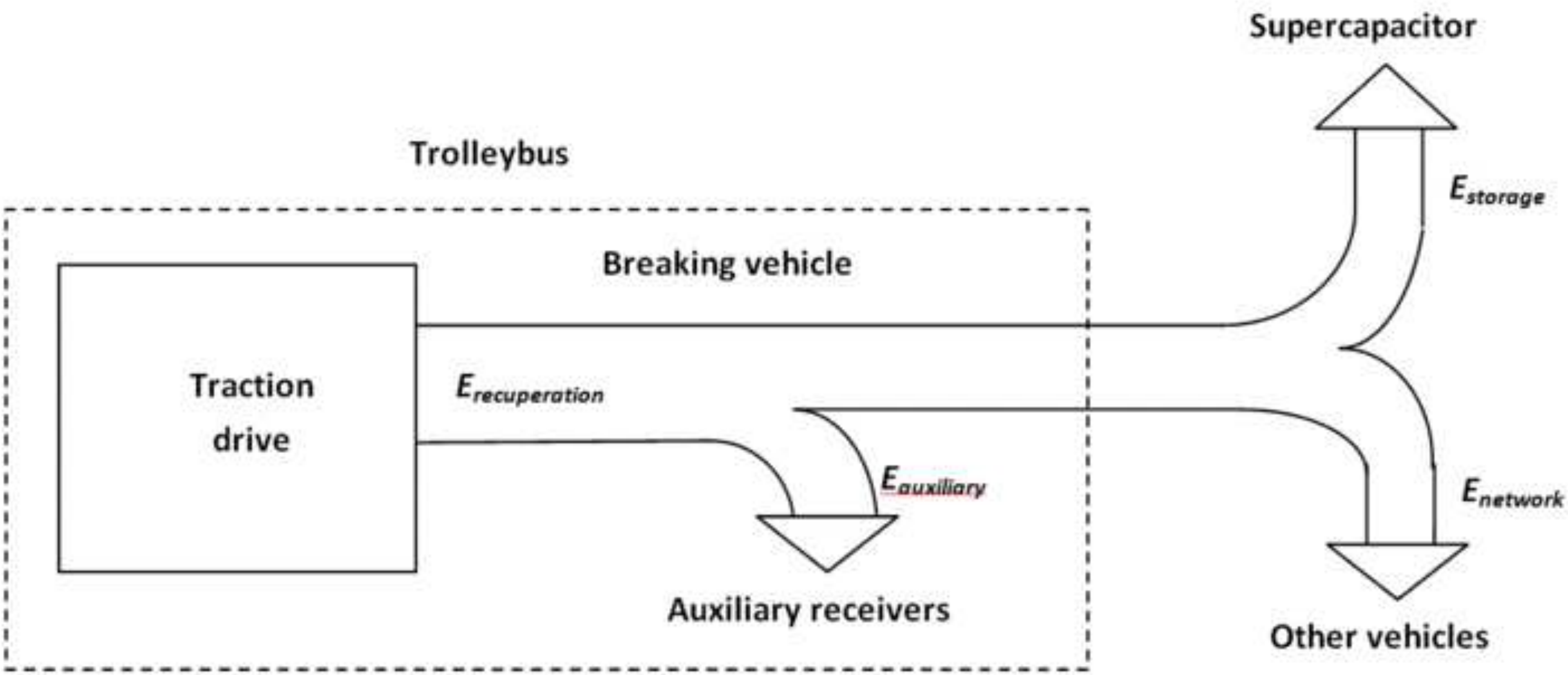

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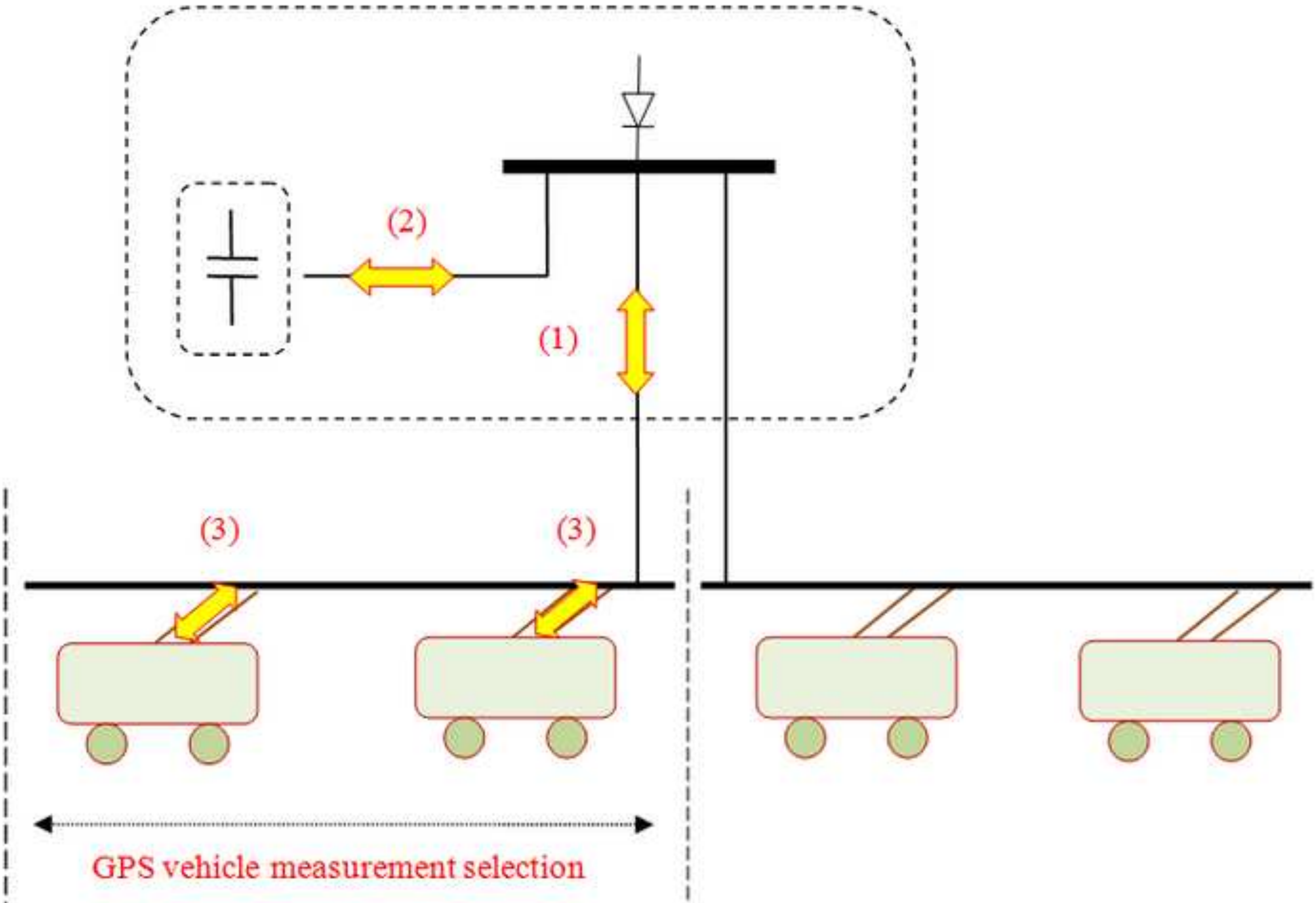

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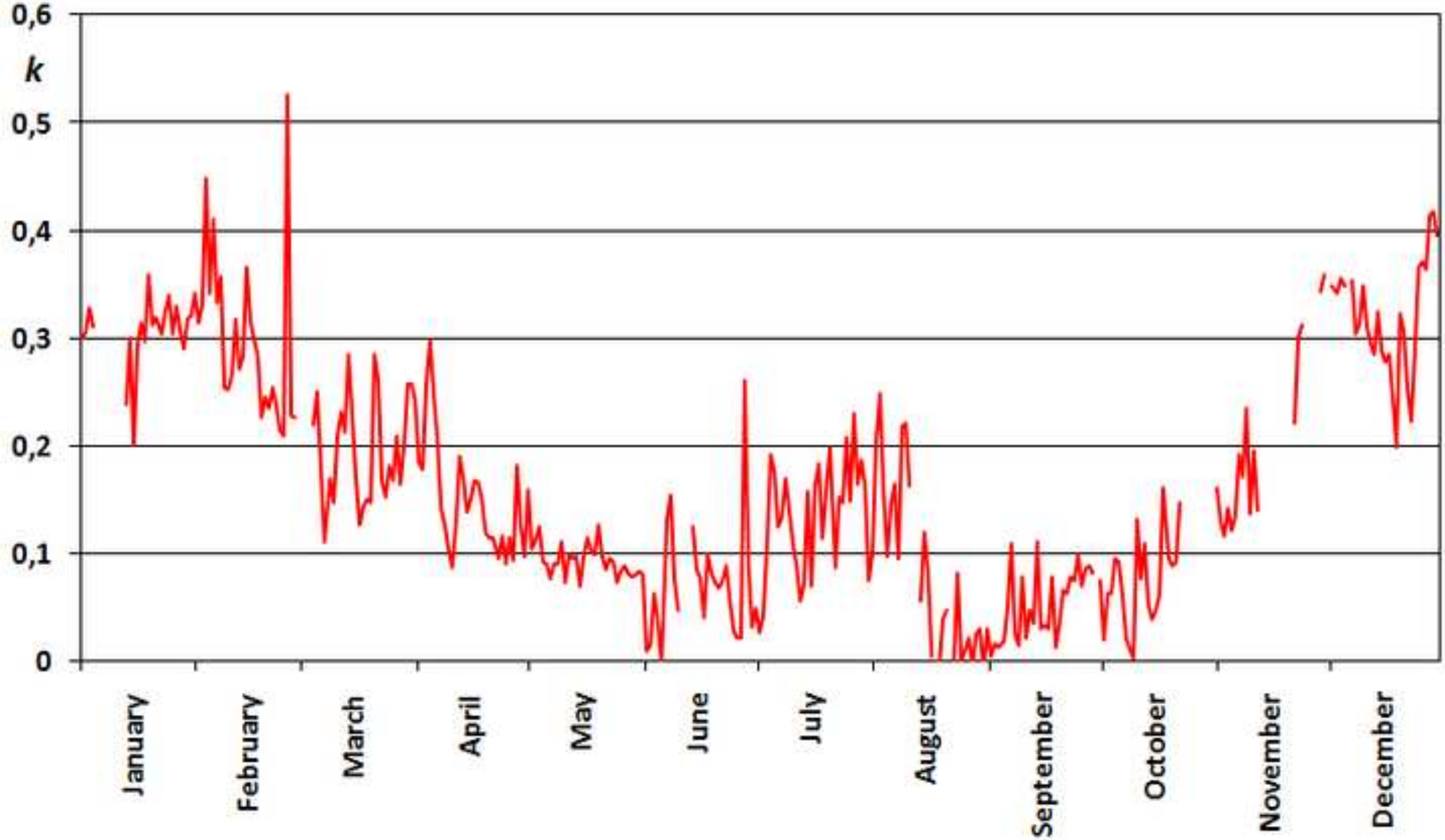

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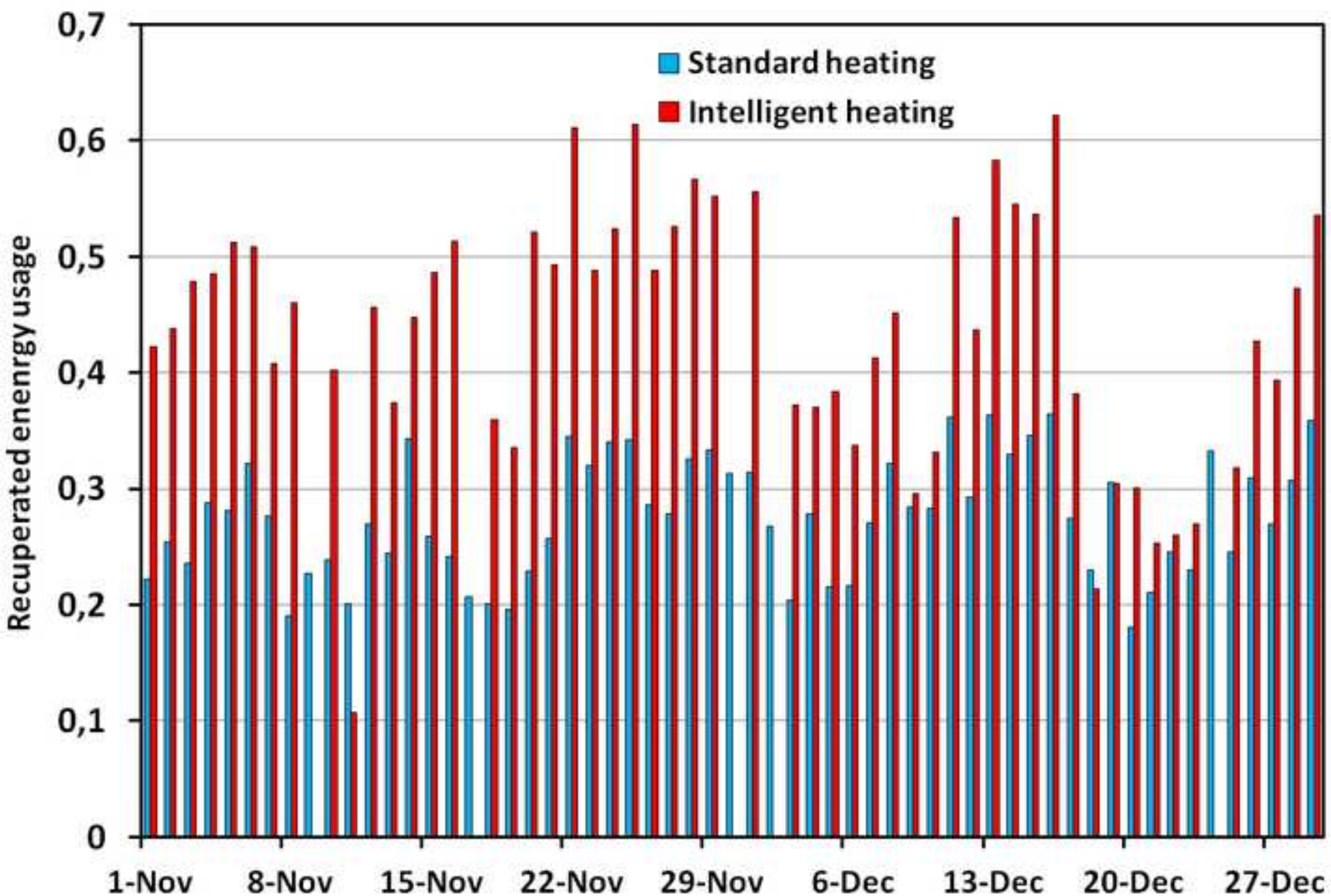

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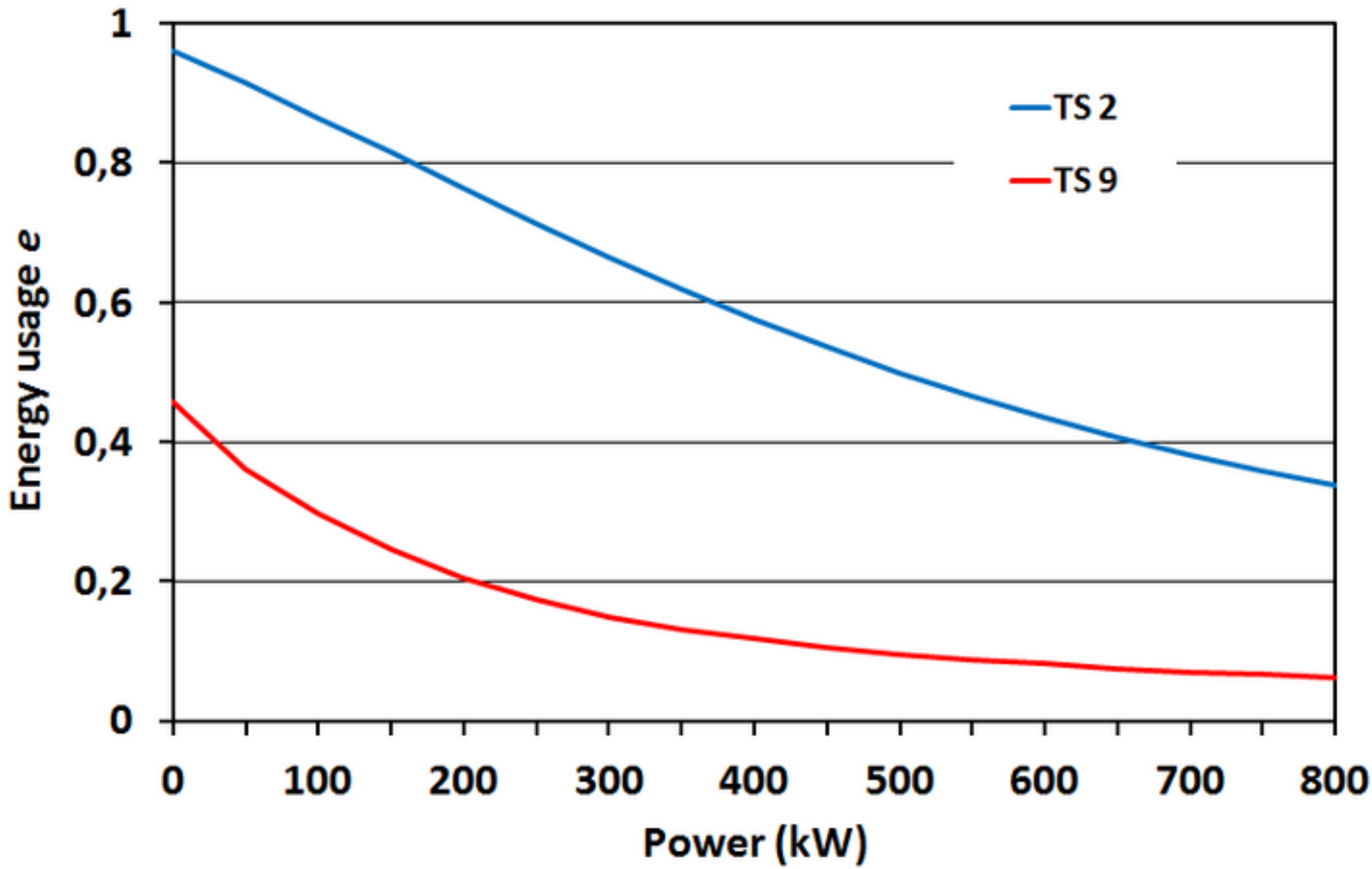

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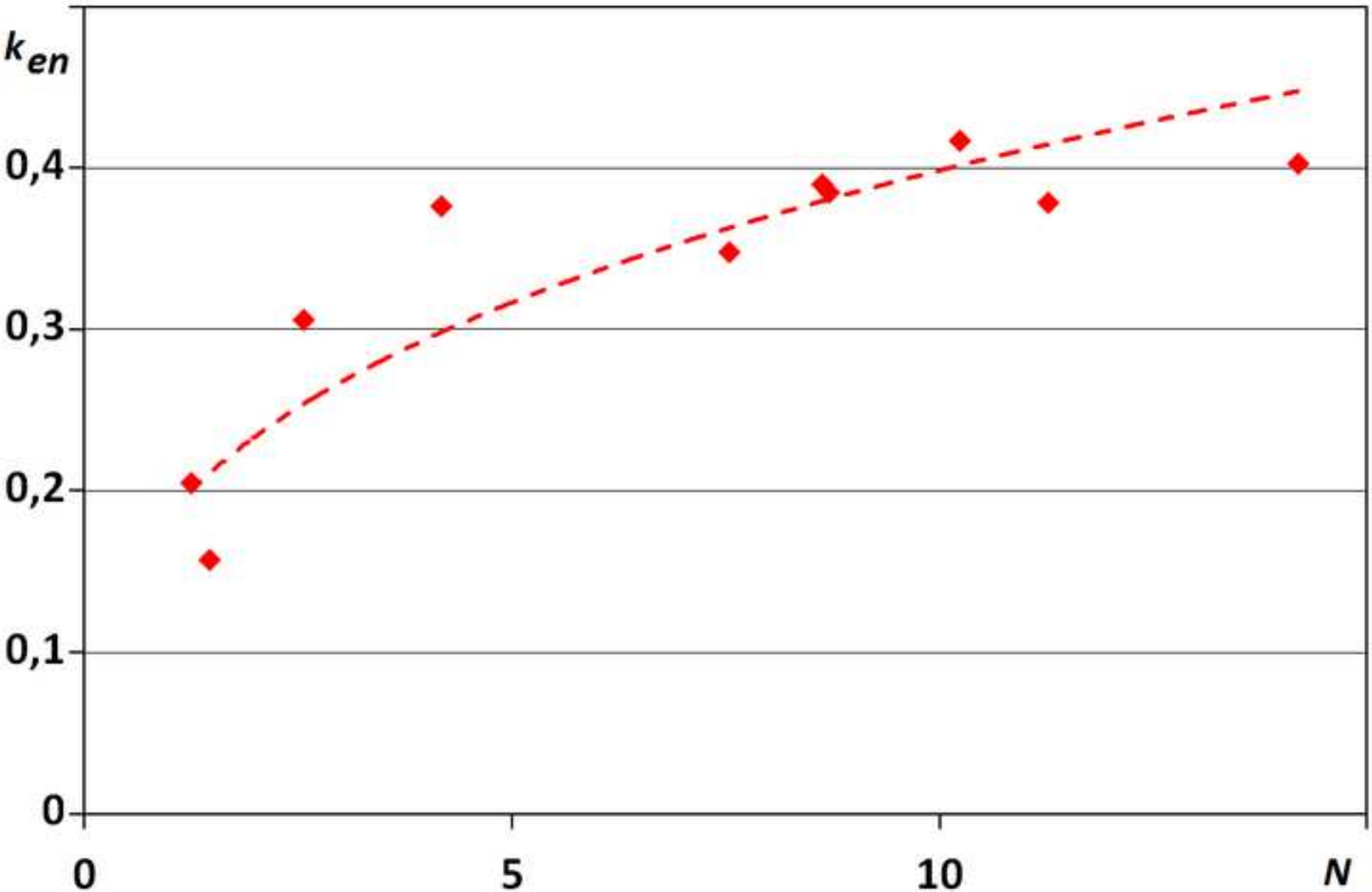

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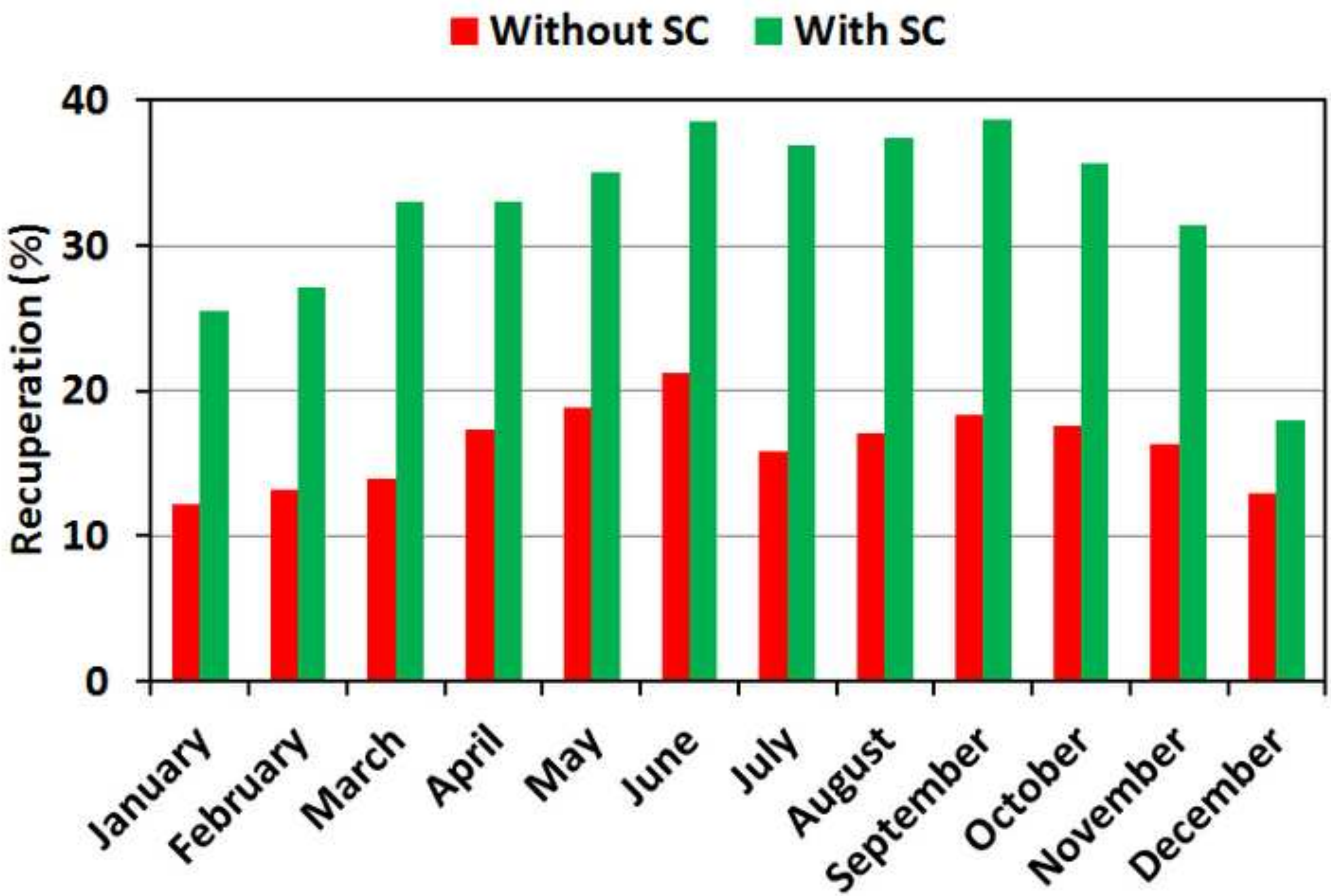

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