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# UTILIZATION OF FLYWHEEL ENERGY ACCUMULATION FOR ELECTRIC TRACTION

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Katedra elektrotechniky elektroniky a zabezpečovací techniky

## 1. Introduction

This elaboration is providing the analysis of a flywheel energy accumulator system at the utilization for electric traction. There are deduced the function conditions and the limitations for the practical using in the rail transport.

## 2. Object of the study

In the ***Fig. 1*** is to see the simplified fundamental structure of the flywheel accumulator system. It is assumed that this system is one and only energy source on the traction vehicle. The charging is possible in some only stopping places which are equipped with special overhaed-line.

## 3. Accumulated energy

For the accumulated energy is valid

$$EFW = 7{,}61 \cdot 10^{10} \cdot M_{FW} \cdot R_{FW}^{2} \cdot (n_1^{2} - n_0^{2}) \quad [kWh] \qquad (1)$$

where is:

$M_{FW}$.................... mass of the flywheel disc [kg]

$R_{FW}$ .................... radius of the flywheel disc [m]

$n_1$ ....................... maximum rpm [$min^{-1}$]

$n_0$ ....................... minimum rpm [$min^{-1}$]

From this formula is evident that the flywheel rpm have a large meaning for the quantity of the accumulated energy. Thanks to the progress in the material technology development is possible now to reach a very high stress tensions in the flywheel disc and trough these also a very high rpm. This positive fact provides a new quality for development of the flywheel accumulator technology and its utilization for electric traction.

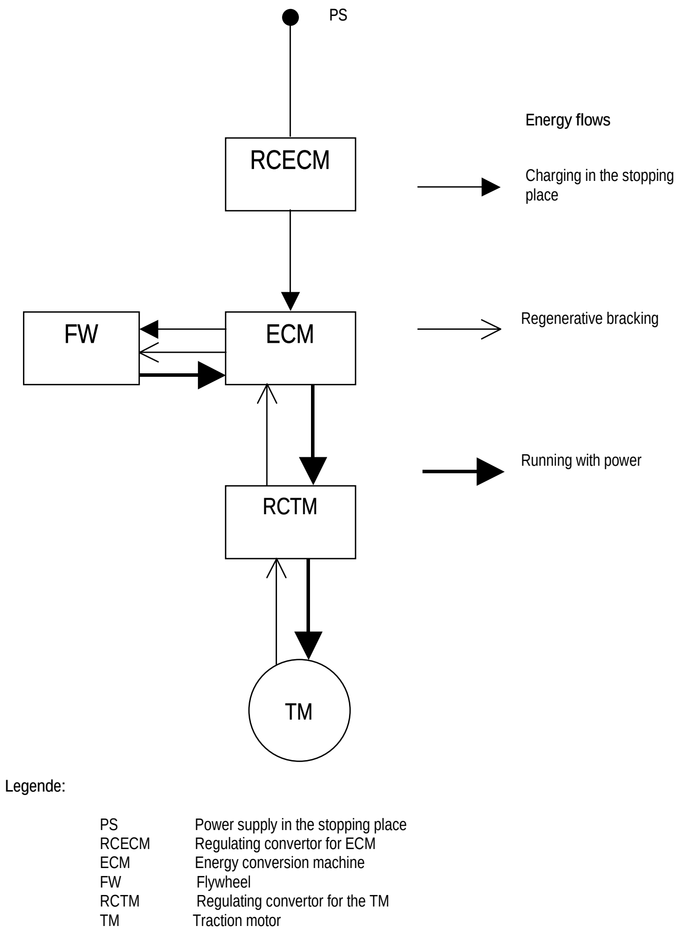



***Fig. 1*** *Structure of a flywheel energy accumulator system*

Diagram in the ***Fig. 2*** shows the accumulated energy depend on the flywheel rpm up to 24 000 min$^{-1}$ - today a wholly normal value. The diagram is valid for $M_{FW}$ = 50kg, $R_{FW}$ = 0,5 m and $n_0 = 0{,}2\ n_1$ (see the formula (1)).

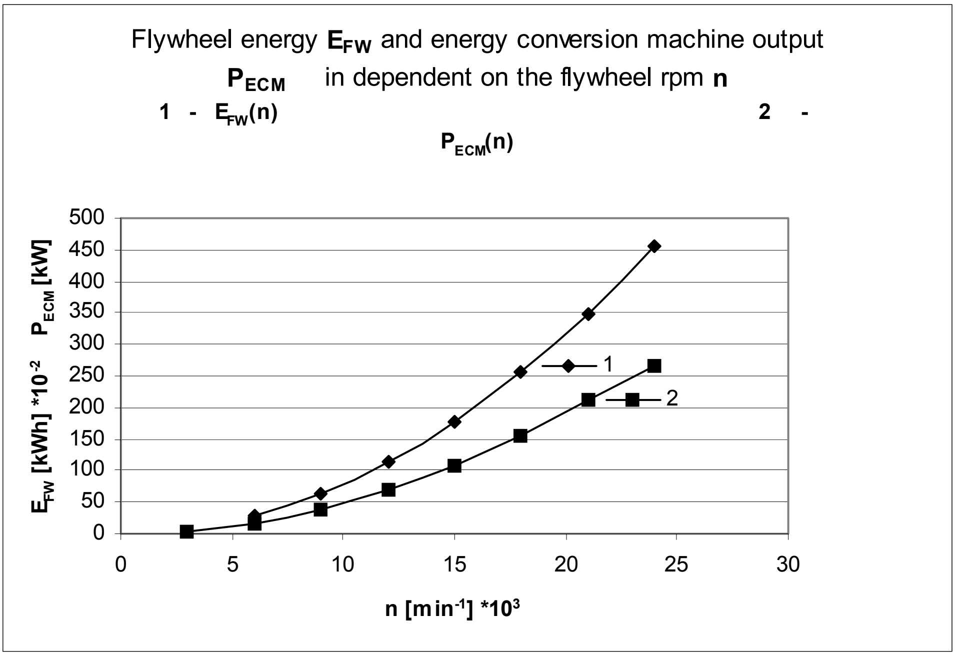



***Fig. 2*** *Flywheel energy $E_{FW}$ and ECM output $P_{ECM}$*

With the flywheel is closely connected a special electric machine – an energy conversion machine ECM which is controlled through a regulating converter RCECM during the charging in the stopping place (see ***Fig. 1***). ***Fig. 3*** provides the view on a really realized flywheel-ECM unit.

For the determination of the power capacity alias ECM-rating is critical the charging time. In this case is the ECM power capacity $P_{ECM}$ given through the formula

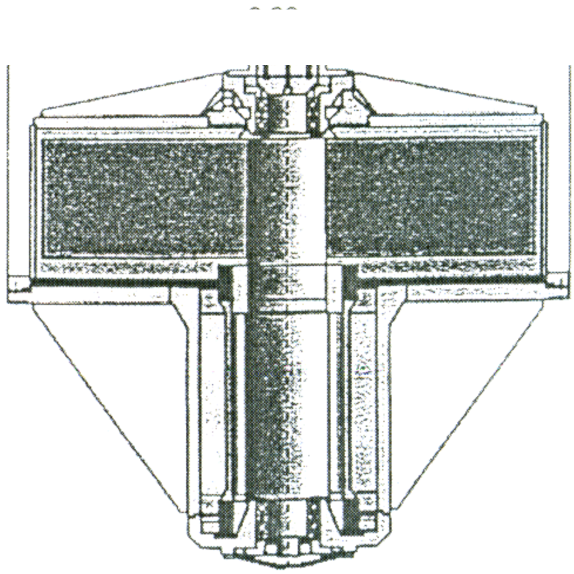
$$P_{ECM} = \frac{E_{FW} \cdot 3600}{t_{ch} \cdot \eta_{FW}} \quad \text{[kW]} \tag{2}$$

where is:

$t_{ch}$ ................charging time [s]

$\eta_{FW}$ .............efficiency of the flywheel [1]

$E_{FW}$ ............see formula (1)



| | |
|---|---|
| Flywheel-disc diameter | 0,70 m |
| Flywheel-disc thickness | 0,16 m |
| Armature length | 0,26 m |
| Armature diameter | 0,125 m |
| Maximum rpm | 25 000 $min^{-1}$ |
| Accumulated energy | 6 kWh |
| Energy conversion machine rating | 300 kW |

***Fig. 3*** *Flywheel - ECM unit*

The dependence of this power capacity on the flywheel rpm for the charging time 60 s is to see in the ***Fig. 2*** too.

The mass of the complete energy source $M_{ES}$, it means the flywheel-ECM unit inclusive accessories is given through the formula

$$M_{ES} = \left(M_{FW} + \kappa_{EMC} \cdot P_{MC}\right) \cdot \lambda \quad \text{[kg]} \qquad (3)$$

where is:

$M_{FW}$ ....................... mass of the flywheel disc only [kg]

$\kappa_{EMC}$ ........................ specific mass of the ECM [kg/kW ]

$P_{ECM}$ ..................... see the formula (2)

$\lambda$ ............................ coefficient respecting the mass of the construction part and accessories of the complete energy source [1]

## 4. Energy and power mass density

The energy mass density of the given complete energy source is

$$\delta_E = \frac{E_{FW} \cdot 10^3 \cdot \eta_{FW} \cdot \eta_{EMC}}{M_{ES}} \quad [\mathrm{kW.t^{-1}}] \tag{4}$$

where is

$\eta_{ECM}$ …………… efficiency of the energy conversion machine [1]

Further quantities are explained in the already mentioned formulas.

For the power mass density is valid

$$\delta_p = \frac{P_{EMC} \cdot \eta_{ECM}}{M_{ES}} \quad [\mathrm{kW.t^{-1}}] \tag{5}$$

Both quantities defined in the equations (4) and (5) have a large meaning for operation characteristics of the traction vehicle.

## 5. Operating range

The operating range corresponding to energy from one charging is given as follows:

$$r = \frac{\delta_E \cdot \mu_E}{e_1} \cdot 10^3 \quad [\mathrm{km}] \tag{6}$$

where is

$$\mu_E = \frac{M_{ES}}{M} \quad [1] \tag{7}$$

where is

M ……… total mass of the complete train consisting of the mass of the traction vehicle and coaches [t]

The quantity $e_1$ is the specific energy consumption on the output from the energy conversion machine. For $e_1$ is valid

$$e_1 = 2{,}72 \cdot \frac{r_0 + g_0}{\eta_0} + 1{,}072 \cdot 10^{-2} \cdot \alpha \cdot \frac{1}{L} \cdot \left[ V_a^2 \cdot \left(1 + \frac{r_a + g_a}{102 \cdot \alpha \cdot a}\right) \cdot \left(\frac{1}{\eta_a} - 1\right) + V_b^2 \cdot \left(1 - \frac{r_b + g_b}{102 \cdot \alpha \cdot b}\right) \cdot (1 - \eta_{rb}) \right] \quad [\mathrm{Wh.tkm^{-1}}] \tag{8}$$

Here means:

$r_o$, $g_o$............ vehicle running resistance and gradient on the whole line between two stops [N/kN]

$r_a$, $g_o$ ........... vehicle running resistance and gradient on the starting acceleration track part [N/kN]

$r_b$, $g_o$............ vehicle running resistance and gradient on the stopping braking track part [N/kN]

$V_a$................ speed at the end of starting acceleration [km/h]

$V_b$ ............... speed at the beginning of stopping braking [km/h]

$\alpha$ ................ coefficient respecting the energetic influence of the vehicle rotation parts – so-called inertia factor [1]

$\eta_0$ ................ efficiency at the running with constant speed [1]

$\eta_a$ ................... efficiency at the starting acceleration [1]

$\eta_{rb}$ ................. efficiency at the regenerative braking [1]

a ................. starting acceleration [$ms^{-2}$]

b ................. braking stopping deceleration [$m.s^{-2}$]

Diagram in the ***Fig. 4*** shows the specific energy consumptions for various operating conditions, which are typical for the passenger trains on local lines. Displayed specific consumption is valid for a light double-coach passenger train-unit which has the mass 40 t with a perfect aerodynamic body form and with a high-performance regenerative braking.

## 6. Running dynamic characteristics

Running dynamic characteristics of a traction vehicle can be expressed trough the highest available speed and through the acceleration at the given speed, trough so-called the final acceleration. Both these quantities should be investigated for various track gradient. For the traction vehicle with a mobile energy source are valid generally following relations.

For the available speed is valid

$$V_A = \frac{\delta_P \cdot \mu_E \cdot \eta_{RCTM} \cdot \eta_{TM} \cdot \eta_{GB} \cdot 367{,}12}{r_v + g} \quad [km.h^{-1}] \qquad (9)$$

Here means

$r_V$ .......................... running resistance in the speed area of $V_A$ [N/kN] g ........................... gradient of the track [N/kN]

Further symbols are explained in formulas (5), (7) and (11)

For the final acceleration is valid

$$a_V = \frac{\delta_P \cdot \mu_E \cdot \eta_{RCTM} \cdot \eta_{TM} \cdot \eta_{GB} \cdot 367{,}12 - V \cdot (r + g)}{V \cdot 102 \cdot \alpha} \quad [\mathrm{m.s^{-2}}] \qquad (10)$$

Here means

V .......................... given speed for the final acceleration determination [km/h]

r ........................... running resistance at the given speed [N/kN]

Further symbols are explained in formulas (8) and (9)

## 7. Total efficiency

Total efficiency of the all energy conversions in case of the surveyed accumulation system can be expressed as

$$\eta_{total} = \eta_{RCECM} \cdot \eta_{ECM}^2 \cdot \eta_{FV}^2 \cdot \eta_{RCTM} \cdot \eta_{(tm)} \cdot \eta_{GB} \quad [1] \qquad (11)$$

when is

$\eta_{RCECM}$ efficiency of the regulating converter for ECM [1]

$\eta_{ECM}$ see the formula (4)

$\eta_{FW}$ see the formula (5)

$\eta_{RCTM}$ efficiency of the regulating convertor for traction motor [1]

$\eta_{TM}$ efficiency of the traction motor [1]

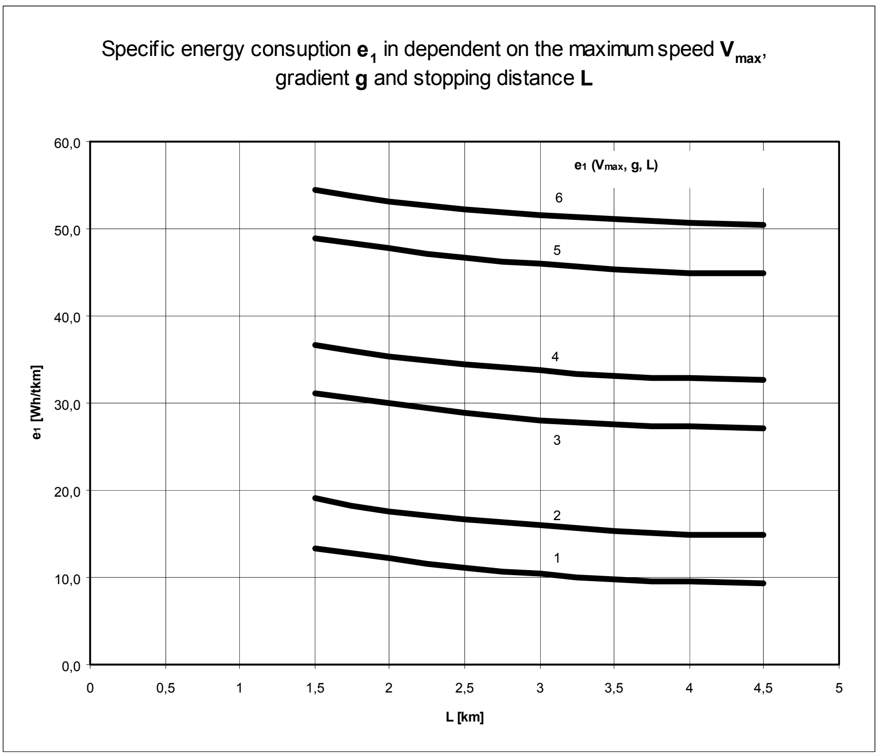
$\eta_{GB}$ efficiency of the gear box [1]

After substitution of typical average values for each partial efficiency we obtain the total efficiency in an interval 0,65–0,7.

## 8. Results of the desk study

The practice example of the given flywheel energy accumulator demonstrate that the using of this technology for electric traction is hopefully. Of course the application area has its specifics and limitations. How are the limitations and possibilities shows an example from rail operation practice. The following results were calculated according to above-mentioned formulas.

Diagram in the ***Fig. 4*** shows the specific energy consumptions for various operating conditions, which are typical for the passenger trains on local lines. Displayed specific consumption is valid for a light double-coach passenger train-unit which has the mass 40 t with a perfect aerodynamic body form and with a high-performance regenerative braking.




1 $V_{max}$ = 60 km/h, g = 0 $^o/_{oo}$
2 $V_{max}$ = 100 km/h, g = 0 $^o/_{oo}$
3 $V_{max}$ = 60 km/h, g = 7,5 $^o/_{oo}$
4 $V_{max}$ = 100 km/h, g = 7,5 $^o/_{oo}$
5 $V_{max}$ = 60 km/h, g = 15 $^o/_{oo}$
6 $V_{max}$ = 100 km/h, g = 15 $^o/_{oo}$

***Fig. 4*** *Specific energy consumption*

Final acceleration for the exemplary train-unit is presented on the ***Fig. 5.*** It is to see, that the running on gradient 15 $^o/_{oo}$ is carried out with the final acceleration 0,13 ms$^{-2}$ at the speed 60 km/h. It means, in other words, that the highest speed can be reached still on gradient 30$^o/_{oo}$.

Operating range for various operation conditions provides the ***Fig. 6***. The points of intersection of the curves 3, 4, 5 and 6 with the curve 7 show the maximum distance between two stopping places with the charging. For example – for the running on gradient 15 $^{o}/_{oo}$ does this distance more as 2 km.

## 9. Conclusion

The most significant result of this desk study is a theoretic verification, that the flywheel energy accumulation system used as only alone energy source on the traction vehicle is usable for the light passenger train operation. It is also important, that this using is possible on the lines with larger gradients and with larger distances between stops.

There are known more successful of this energy accumulation technology, but till this time they were installed in the hybrid system with another energy source. It should be useful to dedicate in the future for this question still research effort and also to study the related economic questions.

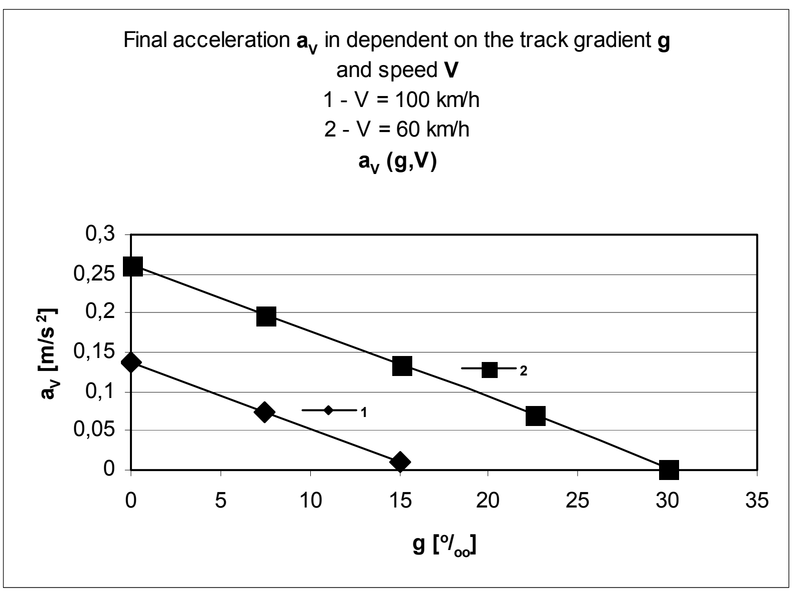



***Fig. 5*** *Final acceleration*

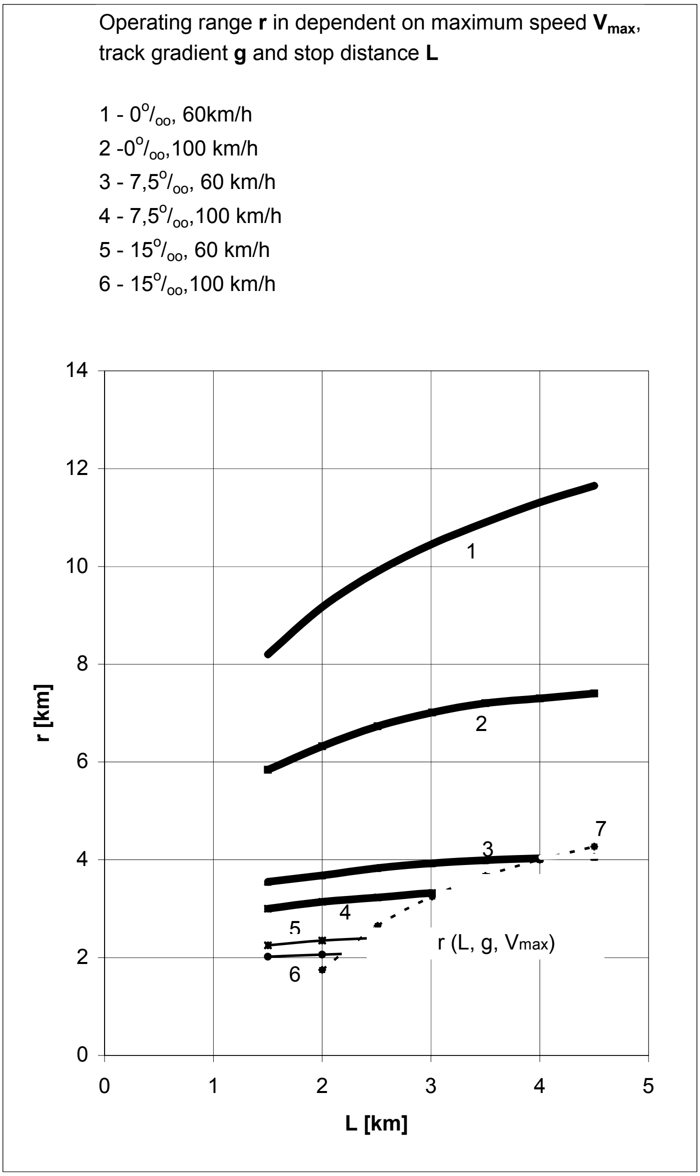



***Fig. 6*** *Operating range*

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**Resumé**

**POUŽITÍ SETRVAČNÍIKOVÉ AKUMULACE ENERGIE PRO ELEKTRICKOU TRAKCI**

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Teoretická studie je věnována otázce použití gyroelektrického akumulačního systému pro napájení kolejového trakčního vozidla. Současné poznatky jak v oblasti konstrukčních materiálů, tak v odvětví elektronických regulačních měničů a elektrických strojů umožňují konstruovat vysokootáčková soustrojí s vysokým měrným hmotným výkonem a energií. Studie předkládá metodiku šetření daného problému a dokumentuje reálnou možnost praktické aplikace zkoumané mobilní zdrojové soustavy, jako jediné a samostatné, na elektrickém trakčním vozidle.

**Summary**

**UTILIZATION OF FLYWHEEL ENERGY ACCUMULATION FOR ELECTRIC TRACTION**

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Theoretic study is dedicated to the question of the using of the flywheel accumulation systém for the power supply of a traction vehicle. The new knowledges in the branch of construction materials, of electronic regulating convertors and of electric machines allow today to design the high-speed flywheel units. These devices have a high power and energy mass density. The study presents the research methodology for solution of the given question. Herewith it proves the possibility for the practic application of this mobil energy source as the only alone on the traction vehicle.

## Zusammenfassung

## VERWENDUNG DES SCHWUNGRAD-ENERGIE-SPEICHERS FÜR DIE ELEKTRISCHE TRACTION

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Teoretische Studie ist der Frage von Verwendung des Schwungradspeichers für die Energieversorgung des Triebfahrzeuges gewidmet. Die neue Erkenntnisse im Bereich von Konstruktionsmaterial, der elektronischen regulierbaren Umrichtern und der elektrischen Maschinen erlauben heute die Hochgeschwindigkeit-Schwungrad-Einheiten zu bauen. Diese Anlagen haben eine hohe Leistung- und Energie-Massdichte. Die Studie legt die Untersuchungsmetodik für die Lösung der gegebene Frage vor. Zugleich sie beweist die Möglichkeit für die praktische Verwendung dieser mobilen Energiequelle als nur einzigen auf dem Triebfahrzeug.