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Alternative Energy Sources Usable in Automotive Transport

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Abstract: The research focuses on the methodology of preparing a concept and application scenarios for alternative sources of energy in transportation. The ideas and interpretations are not strictly limited to automobile transport but also reach into other areas of using and processing energy. The conceptual approach to the choice of sources, with the aim of securing the efficient use of energy conversion, is illustrated on the model embodiment embedded in a passenger car; the relevant presentation is centered on an experiment focusing on the linear arrangement of a driven electromagnetic generator. This involves generating and collecting energy for not only the accumulation of electrical energy using relatively independent systems, but also for direct use within driving needs. In the modeled example, the supplied energy is assumed to be in a range of constant power from p = 10 W to 50 kW (200 kW). The given example of the design of the choice of energy conversion sources and the use of generators in a passenger car shows the possibilities, limitations, and variants for demonstrating the requirements relating to a simple driving mode. The application of a linear or cylindrical internal combustion engine is considered for a specific set mode of the car. Variants of suitable uses of the accumulated energy in compressed air are proposed. The use of light and thermal forms of energy is considered for additional forms. As an experimental example, the use of generators derived from vibration harvesters is shown. The proposed energy generation arrangement can be controlled and optimized for specific transport tasks. The generation and accumulation of energy can be employed in the form of electrical energy, as kinetic energy for direct use in driving, or to accumulate in compressed air for later use. Solar energy can be used directly or can be accumulated. The combustion unit can serve as a source of kinetic energy or also to store energy for further use. The concept of alternative sources is based on known methods of use in other industries. The model combination of resources and its simple analysis in the concept of resource selection is demonstrated on an example of an application in passenger cars.

Keywords: harvesting; pressurized air; electromagnetic field; renewable energy; linear motion; revolver engine; alternative sources of energy; car driving

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1. Introduction

Before 2020, trends in savings, the effective use of primary energy sources, and controlled energy consumption affected most industrial sectors. The main requirements were centered around the independence and substitutability of the energy system, its high yield rate, energy processing efficiency, and the possibility of obtaining other forms of energy using known and applicable conversion principles, all with consistent respect for the laws of the electromagnetic field [1]. Methods for generating and efficiently utilizing energy or concepts to ensure energy conversion/transduction [2–4] have, to date, not covered some newly emerging scientific and technical areas that embrace energy production and processing for its conversion, including the procedures that convert energy into electrical energy. At that time, the set of published and applied approaches included only a limited group of physical principles [5–8] of conversion and the corresponding implemented technical devices [9–12]. Approaches to processing unused forms of energy for the purpose of consumption began to develop [13,14]. However, diverse specific principles and forms of energy conversion and use are known but not technically processed, including, for example, the energy conversion from a flowing medium (water or air) and the conversion of incident high-frequency electromagnetic waves, photovoltaic systems in particular [15–17].

With regard to developments in, for instance, transport, communications, control, and regulation systems, the need for alternative energy sources has to be considered. New conceptual solutions for energy harvesting will be applied in mobile or wireless devices [18–20], sensor-independent systems [3,4], autonomous sensor devices, and systems where a stable power supply is disadvantageous or cannot be ensured [3,4], including the possibility of reducing the requirements in passenger transport (from one-wheeled or two-wheeled to special vehicles). The requirement for parameters of alternative energy sources also focuses on estimating the minimum operating time of the device without a stable (non-mobile) energy supply distribution network. Precisely specified segments of harvesting and converting energy, together with its conversion into electricity, depends on an accurate application of Faraday's law of induction [1], especially for devices using the movement of the system in a magnetic field or with the presence of vibrations [2–6], with the primary rotational or linear motion of the body.

The research of suitable concepts of energy conversion embodies a step that generally allows for the design and use of equipment in a suitable or optimal way. One of the applications of energy rests in its conversion into forms of kinetic energy. A close example is transport in its many forms. In specific means of transport, e.g., electric bicycles, motorcycles, and cars, the energy flows are controlled with an instantaneous power input in the relevant range (from p = 10 W to 50 kW). To date, the electrical form has mostly been used to enable energy conversion. However, this concept brings a number of problematic or expensive technical solutions (such as electromobility). A rational solution for mobility would rest in the use of alternative forms of energy in combination with electricity. For this reason, usable principles are still a focus for technical solutions relying on the use of residual or alternative forms of energy. Such an example can be, among others, the expansion of compressed air or, in engines, the control of the linear movement with a minimum of inertial mass. The possibilities of converting kinetic, thermal, solar, and other forms of energy into electricity, motion, or heat include various approaches and ways of designing conceptual solutions [21–23].

Despite the fact that expensive or non-safe solutions for the energy management of passenger cars are currently being implemented, we show, as a model and a simple example, the use of newly designed reliable, efficient, and safe forms of energy conversion on a rational and predictable basis for a passenger car.

This article demonstrates, on a model set of generators, harvesters, or combined energy sources and accumulating components, the possibility of reducing the required instantaneous power supplied to the system being applied. The methodology is exposed via a concept targeting the usability of the mechanism in passenger cars, with an emphasis on key parameters such as the power volume density in the individual sources. The presently pursued original research of robust harvesters and their overall usability involves exposing the design of a magnetic circuit in a linear electromagnetic generator with a compressed gas engine. Such a combination comprises two central aspects, namely that the electromagnetic part may guarantee a yield rate of up to 2500 times that of the presently used options [18–20,24,25] and that there is a possibility of markedly reducing the energy-related requirement for powering the conceived components.

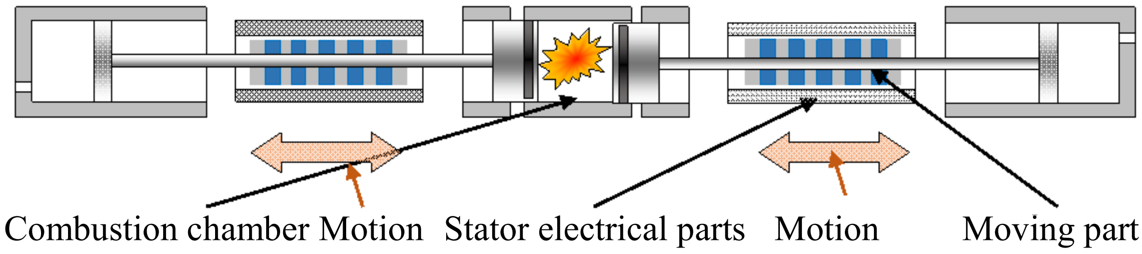
2. Methods of Conversion Applied

Long-term research on the possibilities and principles of converting energy into a useful or usable form leads to the selection of concepts to convert various forms of energy, not just the electromagnetic variant. From this perspective, a wide range of approaches with which to gather and use constant energy are investigated, expanding beyond electrical power in the range from p = 10 W to p = 50 kW. The power range is wide with regard to being used in a broader section of passenger transport than merely cars (from p = 50 kW to p = 200 kW). For example, small transport vehicles that serve humans, such as an automatic vacuum cleaner (propulsion power is required p = 80 W), a skateboard (p = 150 W), a scooter (p = 800 W), a unicycle—InMotion (p = 10 kW), or an electric bicycle (p = 2000 W), can be considered in this regard. Published articles and studies dealing with harvesting can be divided into several groups according to the technical solution of the primary source—drive or engine—and according to the secondary source of energy—generator, according to the methods of analysis engine–generators and according to approaching alternative methods of energy conversion. **The first** group includes the area of the design and solution of the electrical, electronic, and electromagnetic parts of the designed generators; the basic works include works [5–8]. **Another group** deals with the issues of harvester/generator drives, often in relation to the functions and components of the internal combustion engine [9–12]. This is followed by a group that contains articles publishing the possibilities of motion generation, their use for conversion by drifting the electromagnetic part of the generator [13,14], corresponding models [18–20], principles of motion, and suitably performed experiments [24–40]. **Another category** includes methods and procedures of concepts using the linear motion of the drive unit based on the hydraulic transfer of dynamic energy to the motion element, texts related to motion control solutions, and the modeling, simulation, measurement, and evaluation of relevant model parameters.

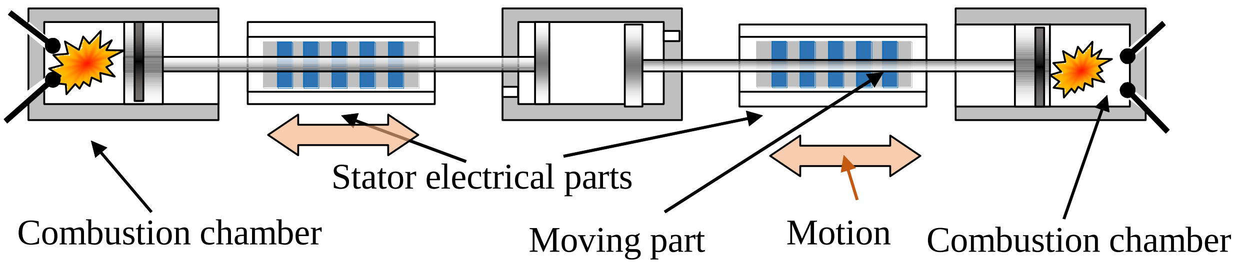
So far, the principle of an internal combustion engine with linear piston movement using conversion to rotary motion without using a crankshaft and with minimal inertia of the moving part of the engine has been largely neglected in applications and technical implementations. This engine concept [22] allows the shaft speed to exceed the minimum to 50,000 rpm without a mechanical gearbox. The possibility of controlled detonation for selected pistons of internal combustion engines with a linear moving element is also very relevant. The consumption of such engines for the planned load power p = 50 kW is one order of magnitude lower compared to a classic internal combustion engine that converts energy to rotary motion using a crankshaft. Thanks to minimal inertia in new concepts of linear combustion units, the efficiency of converting dynamics to motion is significantly more efficient than in conventional internal combustion engines. When designing concepts of energy conversion, it is also necessary to use well-known knowledge from the field of the design and operation of cogeneration units.

One of the research directions leads to the design and solution of the combustion unit in linear engines, namely the free piston engine. This mechanism, unlike the conventional crankshaft engine concept, has only one or two pistons connected on a common shaft [30]. It is characterized by precisely controlled detonation and the smoothing of the dynamics of the movement of the mass of the moving part. The free piston linear engine uses the movement of a common shaft on which a linear electric generator is mounted [41], or, alternatively, a hydraulic piston mounted on a common shaft is used to create hydraulic pressure by moving the piston.

Publications dealing with the construction and testing of a linear combustion engine in conjunction with a generator include work from West Virginia University (USA) [2,4]. These suggest using an electric linear motor as a generator. The concept features good energy conversion efficiency and a compact design [5], which is different to concepts using a rotary engine. The basic elements of a linear generator are a linear internal combustion engine or a free piston engine and a linear "electric motor" producing electricity (linear generator). The combustion chamber [16], equipped with valves, is shown in Figure 1. Another variant of the concept of an efficient internal combustion engine is a piston of an internal combustion engine without a crankshaft and gearbox [22], with the direct conversion of linear motion to rotational motion, as shown in Figure 2. In the 1960s, many patents were published [21–23] with a solution for an internal combustion engine with direct conversion-to-rotational motion without rotor friction masses, as shown in Figure 3. As an alternative to combustion, it is possible to use the energy accumulated in compressed air to create rotational motion, as shown in Figure 4. The accumulation of energy in compressed air and its following use was used in aviation by French companies (for example, Dassault Aviation) from 1912 to 2000 [42]. This alternative energy source and drive is a complementary solution to other appropriately selected and controlled sources of energy conversion in independent systems (car, bus, train, parts of an airplane, ship energy management, etc.).



(a)



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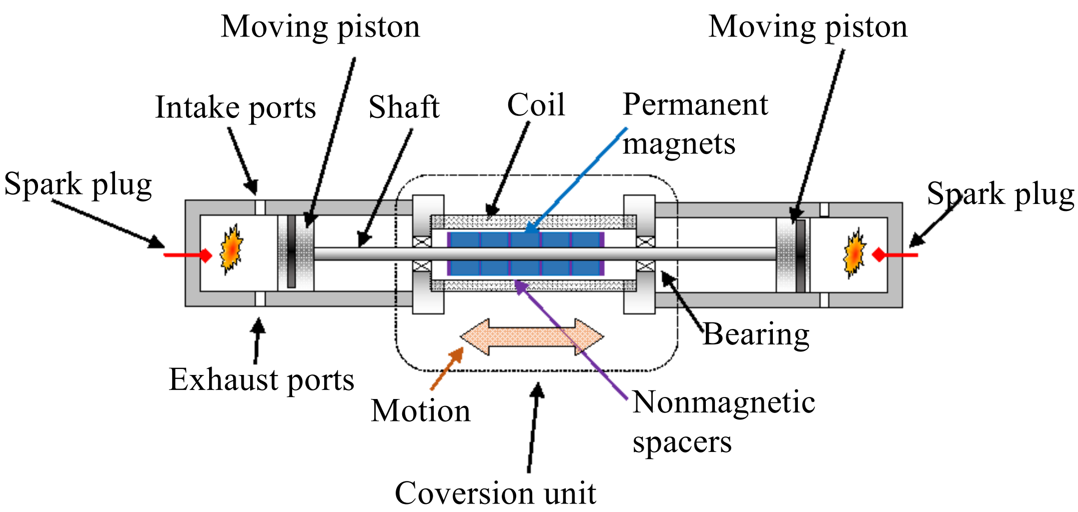


(c)

Figure 1. The design of a linear combustion engine combined with an electric generator: (**a**) two separate units of a linear combustion engine with one combustion chamber and a gas spring, (**b**) two separate pistons in a cylinder with a common gas spring in the middle, (**c**) a linear combustion engine with the combustion chambers on opposite sides.

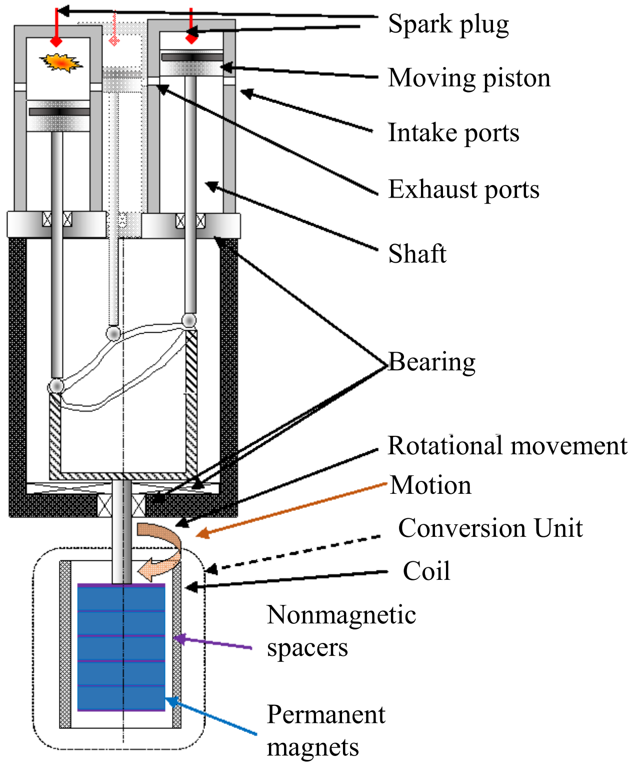


Figure 2. The structure of an alternative combustion engine with linear-to-rotary motion conversion without a gearbox.

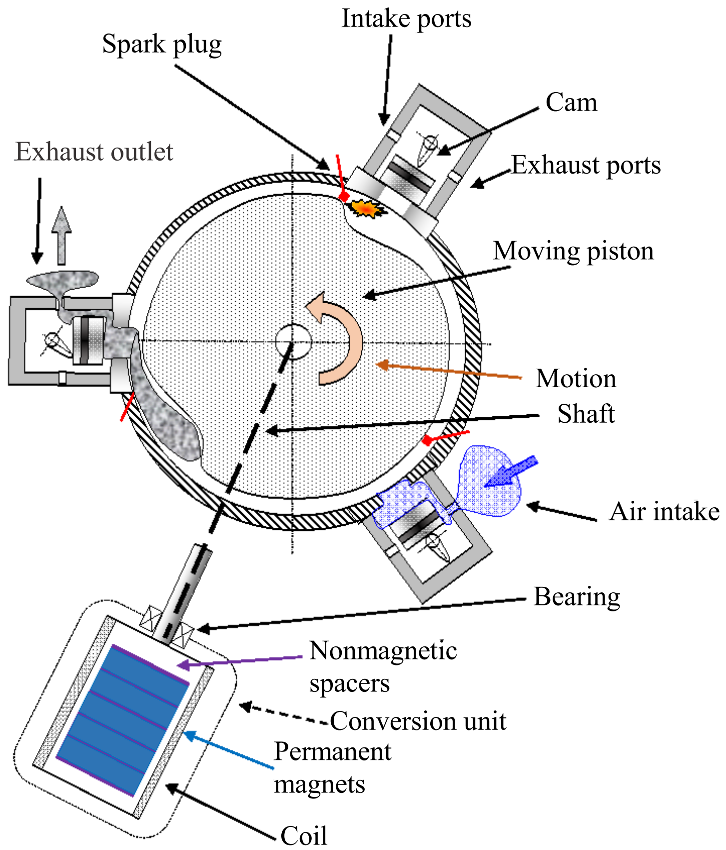


Figure 3. The alternative combustion engine design: a rotary engine without pistons and a gearbox.

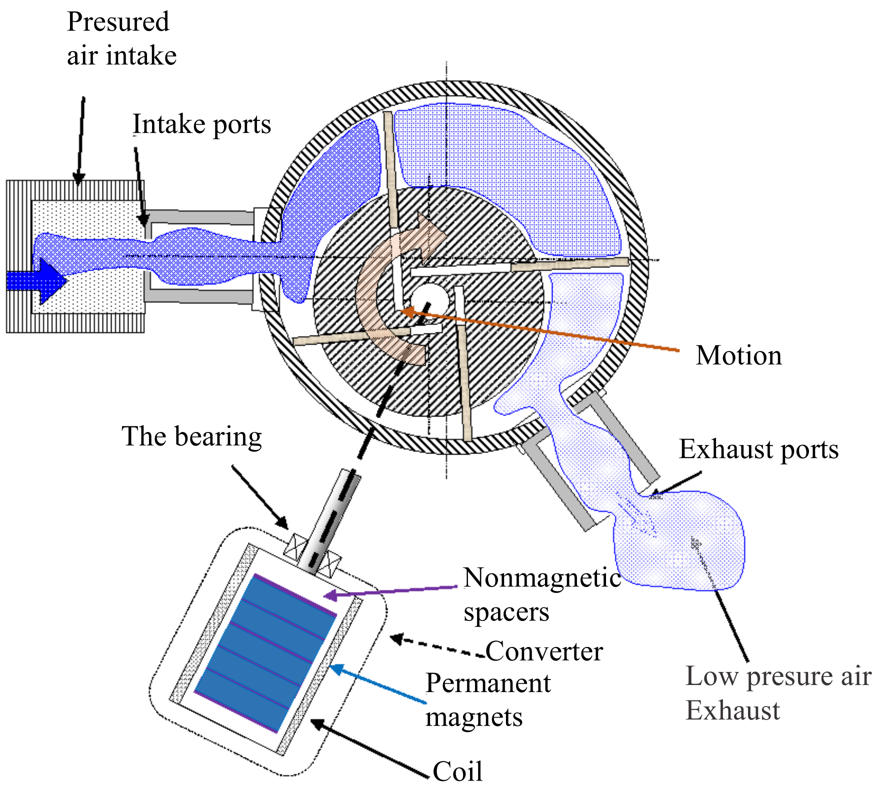


Figure 4. The design of an alternative non-combustion engine without a gearbox and vane air motor.

The disadvantages of energy transformation sources that have been employed to date or are being designed presently rest in the following points:

(A) insufficient options in setting the optimum parameters of converters that transform energy into electrical energy;

(B) a lack of attention paid to and applications of known effects in combustion units, namely effects that are directly associated with further processing stages (thus, for instance, high-pressure gas generation has not been sufficiently employed to date in relation to concepts such as linear engines, as shown Figure 1);

(C) energy sources are often selected on a random basis without systematic premeditation. In confined spaces or upon weight limits, a major parameter to facilitate selecting the source type is power volume density, p_{efd}.

Requirements for an efficient energy conversion solution, e.g., with electrical energy, are based on a basic analysis of the arrangement of the technical design of the converter. In the considered case, an internal combustion engine with a generator for both the linear and rotary arrangement or linear to rotary conversion is used (Figures 1–3). An essential parameter in the design of an energy conversion device is its achievable output power P. The power should also be further usable for energy recovery or accumulation (accumulation, for example, into compressed air, as shown in Figure 4 or by charging an electric battery). Such designs are assumed to have usable energy; for the model example of a passenger car, this would be in the range from W = 20 kWh to 100 kWh. For correct decision-making and a combination of energy conversions, it is necessary to accept the use of media and sources with an achievable effective power volume density p_{efd} [W/m^3], as shown in Table 1. A simple estimation of the energy stored in compressed air, as known, for example, from [43], with its following usage is formulated in Relation (1) as

$$W_{1m3} = p_B V_B ln\left(\frac{p_A}{p_B}\right) + V_B(p_B - p_A) \quad (1)$$

where W_{1m3} is the energy of compressed air of volume V_B, p_B is the initial value of the air pressure, p_A is the final value of air pressure, and V_B is the volume of compressed air. Then, when substituted into Relation (1), the energy $W_{1m3} = 7.0 \times 1 \times \ln(0.1/7.0) + 1\times (7.0 - 0.1) = -22.8$ MJ/m^3. For convenience and simplification, the power volume density lasting 1 s is then the energy volume density given in Ws/m^3, which is therefore one Joule/m^3 (J/m^3), for illustration.

Table 1. The basic parameters of selected sources for "power generation" derived from engineered designs.

Type of Source, Reference	* Effective Power Volume Density p_{efd} [W/m^3]	** Effective Mass Volume Density [kg/ m^3]
Lith. battery [38]	$\approx 4 \times 10^7$	≈530
Peltier unit [39]	$\approx 2.2 \times 10^6$ @ΔT = 72 K	≈5800
Supercap [3]	≈3−5	≈880
Photovoltaic cell [44]	≈200 [W/m^2] ≈ (4 × 10^4 [W/m^3])	≈2320
Presured air [25]	$\approx 2.28 \times 10^7$ @$p_{A\text{-}B}$ = 7 MPa	≈1.3 (50)
Fuel (organic fuel) [25]	$\approx 4 \times 10^9$	≈750
U_{235} [25]	$\approx 9 \times 10^{16}$	$\approx 19 \times 10^3$

* Performance achievable with a known volume of technical design. ** Bulk density related to a known technical solution and design.

The energy stored in the volume of the selected technically implemented storage system V = 1 m^3 for a time t = 1 s then determines the approximate power volume density p_{efd}, as shown in Table 1.

3. Energy Conversion Method Design and Combinations of Methods

For the efficient (optimal) design of energy use and energy sources, it is necessary to know the energy conversion diagram for a moving system with the mass m. This time course then largely determines the choice of sources and conversion elements and mechanisms of the energy management of the system (train, rail vehicle, car, etc.).

An exemplary selection of energy sources and generators can be seen in Table 1. The choice is then governed by the size of the effective volume density of the performance of technical designs suitable for means of transport, such as a passenger car (Figures 5–7). Figures 5–7 only indicate conceptual approaches and possible applications of resources, the selection of which depends on several parameters and expected driving characteristics. The choice also depends on the climatic conditions and the weather for which the car is being prepared. A solar cell or a Peltier cell can be used as an alternative aid for recharging electric batteries. The advantages of energy storage in compressed air can be seen in Table 1. Compressed air is easy to use for conversion for vehicle movement, but in the case of the maximum SOC (State of Charge) of electric batteries, these are able to store "redundant" energy by means of an electric high-pressure pump (max pressure p = 7 MPa). The solar cell as a power volume density (convertible to energy) source has lower power volume density (which can be converted into energy) than compressed air, as shown in Table 1. $p_{efd,sol} = 4 \times 10^4$ W/m^3, which is more than other sources (for example, for five orders of magnitude less than in an equivalent volume of organic fuel, $p_{efd,fuel} = 4 \times 10^9$ W/m^3). The solar cell is therefore 100,000 times lower in power volume density $p_{efd,sol,}$ and therefore its use as an additional energy source is recommended. To address the high energy efficiency of all sources and generators used, as shown in Figure 7, it is appropriate to use a control unit programmed to manage the accumulation and consumption of energy in known scenarios of predictable and unpredictable situations and operations during vehicle operation. For example, it is also appropriate to use tools for the recovery of heat generated during vehicle operation and thus increase the efficiency of energy flow utilization. For example, the heat of the combustion unit cooled down in radiator and exhaust gasses is one of these heat sources, possibly additionally cooling the solar panel. The energy collected this way can also be stored in an electric battery or in a compressed air tank.

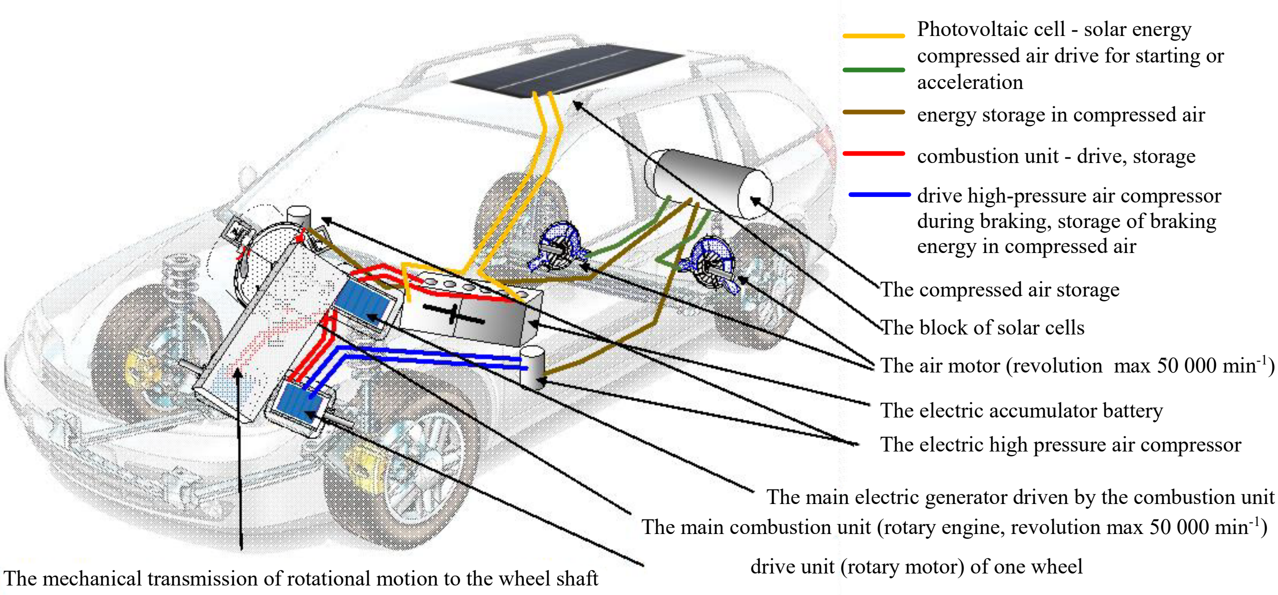


Figure 5. The design of alternative generators in a car with a combustion unit using a combination of electric and mechanical drive, ensuring the accumulation of energy during starting and braking using compressed air.

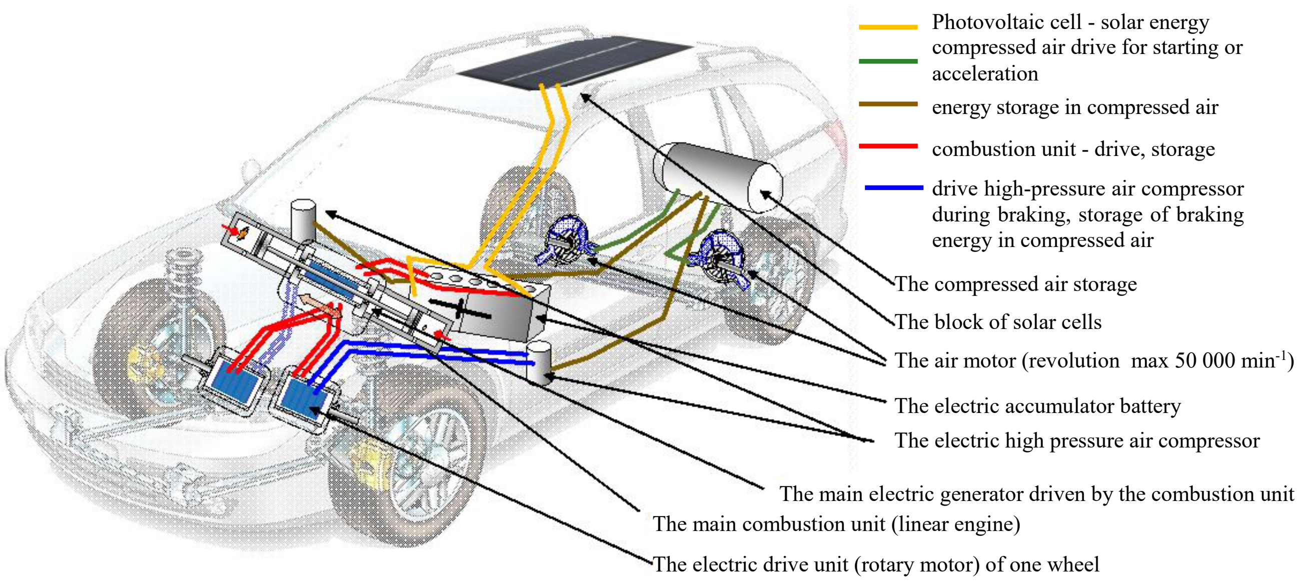


Figure 6. The design of alternative car generators, with linear piston unit electric drive, ensuring the accumulation of energy during starting and braking using compressed air.

The first of the two basic concepts of energy usage is in the selection of the source with a high power volume density and its conversion to movement with respect to the use of an "alternative form of energy" (volume price per unit of time). Such a captured power capacity is afterwards transformed and covers the requirements of consumption according to the driving parameters (for simplicity of the starting, moving, and braking of the car).

The second concept consists of the consistent management and knowledge of the energy flows of the model and their use for the movement of the vehicle at its expected driving dynamics (for simplicity of the starting, moving, and braking of the car).

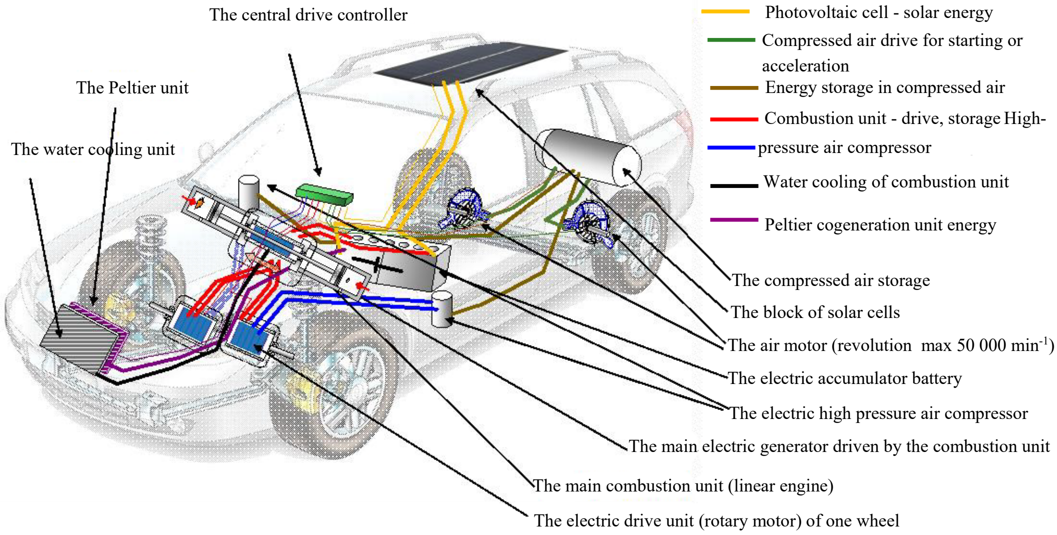


Figure 7. The design of alternative car generators, with linear piston unit electric drive and a Peltier unit, ensuring the accumulation of energy during starting and braking using compressed air.

As a basic model of the motion equation [3,8,18–20] for both conceptual approaches, a mathematical model of the movement of a mass body can be used and expressed in the form

$$m\,a + l_c\,v\; + k\,x = F_{mg} + F_{mech} + F_{alt}, \tag{2}$$

where m is the mass of the body of the car, a is the acceleration of the car body, l_c is the coefficient of the damping of the body's motion (inertia of motion units, etc.), v is the instantaneous velocity of the body, k is the stiffness coefficient of the system (represents friction during the movement of the body and its braking, such as by the resistance of the medium in which it moves, and for example, for the movement of a passenger car, we can model dynamic air resistance and the braking of the body's movement, etc.), F_{mg} are the forces moving the body obtained by the conversion of electromagnetic energy, F_{mech} are the forces moving the body obtained by the conversion of mechanical energy, and F_{alt} are the forces moving the body obtained by the conversion of alternative energy sources (renewable), such as, for example, those accumulated in electrochemical cells, accumulated in compressed air, or obtained from solar energy. For simplicity, the relationship between the force F and the source energy W for further conceptual consideration is given by the relation

$$W = F \cdot v \cdot t, \tag{3}$$

where t is time. The energy W and its acquisition (from a generator, harvester, accumulator, etc.) for an ideal device without friction and (aero)dynamic losses consist of a kinetic W_k and a potential part W_p, which can be expressed as

$$W_k = \frac{1}{2} m_g\, v_g^2, \tag{4}$$

$$W_p = m_g\, g(t)\, x_g, \tag{5}$$

$$\frac{1}{2} m_g\, v_g^2 + m_g\, g(t)\, x_g = F \cdot v_g \cdot t, \tag{6}$$

where x_g is the position in the direction of gravitational acceleration g(t), v_g is the speed of the moving element of the generator, and m_g is the mass of the moving element of the generator. Then, the component F_{alt} and F_{mech} from Relation (2) can be written for the problem of planar motion or idealized bearing (x_g = 0) in the form

$$F_{mech,alt} = \frac{1}{2t} m_g\, v_g. \tag{7}$$

Electromagnetic forces [1] are obtained from the expression of Faraday's law of induction.

$$\underbrace{\oint_{\ell} \boldsymbol{E}(t) \cdot d\ell}_{-\delta\Phi/dt} = -\int_{S} \frac{\partial \boldsymbol{B}(t)}{\partial t}\, dS + \oint_{\ell} \left(\boldsymbol{v}_g(t) \times \boldsymbol{B}(t)\right) \cdot d\ell \tag{8}$$

where $\boldsymbol{E}$(t) is the vector of electric field intensity induced in the vicinity of the magnetic field (electric conductor), l is the length of the field line, $\boldsymbol{B}$(t) is the vector of magnetic induction, S is the area enclosed by the curve l, Φ is the magnetic flux, and $\boldsymbol{v}_g$(t) is the velocity vector of the active part of the generator. Furthermore, the energy of the magnetic field of the generator/motor can be expressed as

$$W_{mg} = \int_{V_M} \frac{1}{2} B_M H_M \, dV, \tag{9}$$

where B_M, H_M are the magnetic induction and intensity at the working point of the magnet and V_M is the volume of the magnetic part. Then, the force entering the dynamics of system (2) can be expressed as

$$F_{mg} = \frac{1}{2 v_g t} \int_{V_M} B_M H_M \, dV. \tag{10}$$

By placing forces F_{mg}, F_{alt} and F_{mech} into Relation (2) and adjusting to a differential expression yields the expression

$$m \frac{d^2 x}{dt^2} + l_c \frac{dx}{dt} + k\, x = \frac{1}{2 \frac{dx_g}{dt} \Delta t} \int_{V_M} B_M H_M \, dV + \frac{1}{2t} m_g \frac{dx_g}{dt} \tag{11}$$

This relationship and its notation of the expression of the dependence between the movement of a vehicle of mass m along a straight section and the energy source result in several usable parameters and principles for choosing a technical solution for a generator for energy conversion. The main criterion for the selection of the source consists of achieving the maximum value of the right-hand side in Equation (11) while maintaining the minimum volume V. Therefore, an overview of some solutions can be seen in Table 1.

(A) A magnetic field generator with a usable force F_{mg} should have small deviations in the direction of gravity x_g so that unusable energy does not accumulate during this movement.

(B) If the parameters of the magnetic flux density and intensity B_M, H_M are achieved in a short time, the effect of the magnetic force of the source on the vehicle's motion system is significantly enhanced.

(C) For mechanical energy conversion and alternative sources, it is necessary to ensure the smallest possible mass m_g of the moving element v_g (motor rotor, common shaft, etc.) of the active part of the generator.

Some concepts of combustion units do not yet comply with the above principles (for example, the crankshaft and inertial masses of the rotational movement of the engine shaft, etc.). Therefore, the development of combustion units is currently turning and focusing on other solutions, as shown in Figures 1–4. Classic electric generators based on rotational movement are replaced by linear systems [25], which show higher conversion efficiency due to the reduction in the mass m_g of the moving part of the generator and the achievement of higher speeds of movement of the active part of the generator, as can be seen from relation (11).

4. A Conceptual Approach to the Choice of Energy Sources for Vehicle Propulsion

The first conceptual approach can be, with regard to the choice of sources and the conversion of energy into car motion, formulated as follows. For example, for the case of a passenger car with a mass of m = 1000 kg, a maximum achievable speed of v_{max} = 150 km/h, a maximum achievable acceleration of a_{max} = 30 m/s^2 (for a speed v_{start} = 0 km/h to v_{stop} = 100 km/h in time t = 3 s), the choice of energy sources at an equivalent maximum system power P_{max} = 200 kW is as follows:

A. For the combustion unit, p = 5 kW–30 kW, the fuel is of the organic fuel type, $p_{efd,fuel}$= 4 × 10^9 W/m^3, and the power volume density of the source is ρ = 750 kg/m^3.
B. The compressed air, p = 30 kW–300 kW, accumulated $p_{efd,air}$ = 2.28× 10^7 W/m^3 and the power volume density of the source is ρ = 1.3(50) kg/m^3;
C. For the electric battery, p = 5 kW (electric charge Q = 70 Ah), using lithium polymer, $p_{efd,elect}$= 4 × 10^7 W/m^3 and the power volume density of the source is ρ = 530 kg/m^3,
D. The solar panel (S = 3 m^2), p = 600 W, displays continuous accumulation into compressed air and battery electric energy, where $p_{efd,solar}$= 4 × 10^4 W/m^3 and the power volume density of the source is ρ = 2320 kg/m^3.
E. The Peltier unit (V = 0.001728 m^3), p = 7.6 kW (ΔT = 72 K), displays continuous accumulation into compressed air and battery electric energy, where $p_{efd,Peltier}$= 2.2 × 10^6 W/m^3 and the power volume density of the source is ρ = 5800 kg/m^3.

For sources A–E, it is possible to use devices that use the principles of energy conversion and are already mentioned above in this text. For example, the combustion unit from Figures 1–3 allows us to apply both linear motion with energy conversion to electric batteries and compressed air and to directly use rotational motion to move the vehicle. It is also suitable for combination with additional wheel drive. Compressed air is a very efficient storage element with a peak power P_p in the order of hundreds of kW with a usable storage volume V [45]. When using appropriate air aggregates for converting air pressure into motion, e.g., from Figure 4, as an air motor, the solution meets the previously required energy distribution parameters. At an air-driven unit power of p = 15 kW, the corresponding volume of one motor, Figure 4, is theoretically $V_{teo,air}$ = 0.65 dm^3, practically V_{air} = 1.3 dm^3. The electric battery and its design can be used with the already known classic design with a capacity of Q = 70 Ah, but, for a safe reserve of capacity and peak consumption, it is recommended to design a battery with an increased capacity of Q = 120–140 Ah. For source D, the solar panel, its use as an additional source of electrical energy, as an accumulation tube for charging the electric battery and accumulating energy in compressed air, even when the vehicle is idle, can be considered. This provides a supply of compressed air for moving the vehicle by releasing the energy of compressed air. Source D can also work when the vehicle is idle without the support of other energy sources. For the most effective evaluation of the residual heat energy of the combustion unit, a Peltier cell is used, as shown in source E. When respecting the power volume density, shown Table 1, the Peltier cell represents an effective tool for the conversion of unused thermal energy. This is a supplement to an effective way of accumulating thermal energy, both while driving and after the vehicle stops (when the operating media cool down, etc.). The transformed heat can be accumulated, for example, in a compressed air tank or electric battery. In this concept of the distribution and use of energy sources at points A–E, the parameters and type of the combustion unit can be changed to a certain extent and, consequently, so can the power of all deployed sources. For the selection and distribution of power to selected energy sources, it is appropriate to **use the second conceptual approach**.

The concept of sources, based on the distribution of the choice of instantaneous energy sources in the car, assumes the following effects on its parameters:

(A) **The production price** of a car can be significantly reduced compared to a car with only electric drive, even with the so-called hybrid drive. This consists of a combustion unit with a connected electric drive. The accumulation of energy in compressed air and its subsequent use is neither economically nor technically demanding. Additional sources (Peltier unit, solar panel, etc.) will help to significantly reduce the cost and volume of combustion units.

(B) The combined power source concept is expected to **result in weight** savings compared to using a purely electric drive. In Table 1, the power volume density parameter can be supplemented with the mass volume density. The resulting solution then evaluates the weight requirements for its limits. With an optimal design, the new solution can reach below the weight limit of a car with only an internal combustion engine.

(C) The **dynamic properties** of alternative sources are different. But the use of compressed air gives great possibilities for achieving high dynamics with the car. This drive was used in aviation in various modifications (until 2000 [42]), even where the electric drive did not meet the demands for peak performance.

If we were to approach the above comparison criteria using the example of car variants with the major power source type, we could obtain a weight comparison and a very approximate price estimate. Consider a passenger car with a maximum power of p = 250 kW, basic car body weight of m_0 = 800 kg, and operating time of T = 1 h. Let us consider the following drive variants:

(1) A lithium battery storage without a combustion unit;
(2) A small combustion unit and compressed air;
(3) A classic combustion unit and organic fuel.

Using Table 1, for operation T = 1 h with power p = 250 kW for design variants (1) to (3), the following approximate **comparison of car weights** can be obtained:

(1) m_1 = 1300 kg, (2) m_2 = 1000 kg, and (3) m_3 = 1600 kg. The comparison includes the accumulation of the weight of the technical solution of the energy source, the design of the auxiliary equipment, and the weight of the basic car body m_0.

If we were to compare the design variants according to **volume requirements**, shown in Table 1, the following estimate can be obtained:

The volume of V_1 according to (1) is comparable to the variant V_2 (2). The smallest volume requirements are for variant V_3 (3). The volume of V_3 is an order of magnitude lower than the volume V_1 of variant (1). The V_3 volume is comparable to the V_2 volume requirements of variant (2).

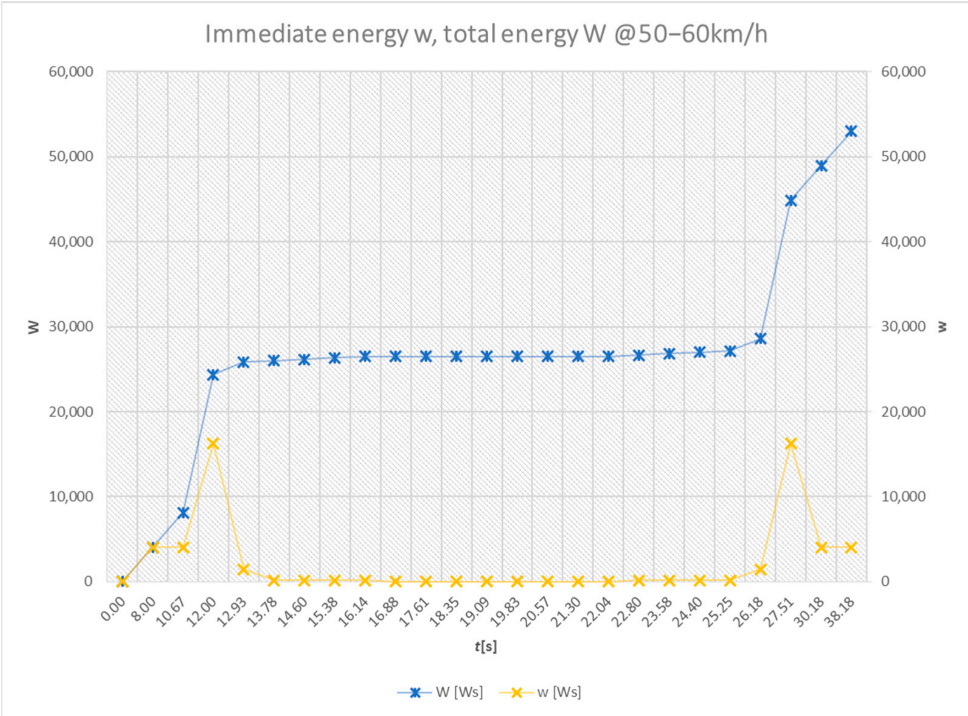
The **price comparison** of the considered variants is very approximate and difficult to calculate precisely. It depends both on the achievable production technologies and the cost of maintenance and development. However, if we were to compare only the price of the production costs plus the operation of the mentioned variants, we would probably achieve the following rating:

According to the current estimates of final prices on the market, the comparison for the same delivered volume of energy is as follows:

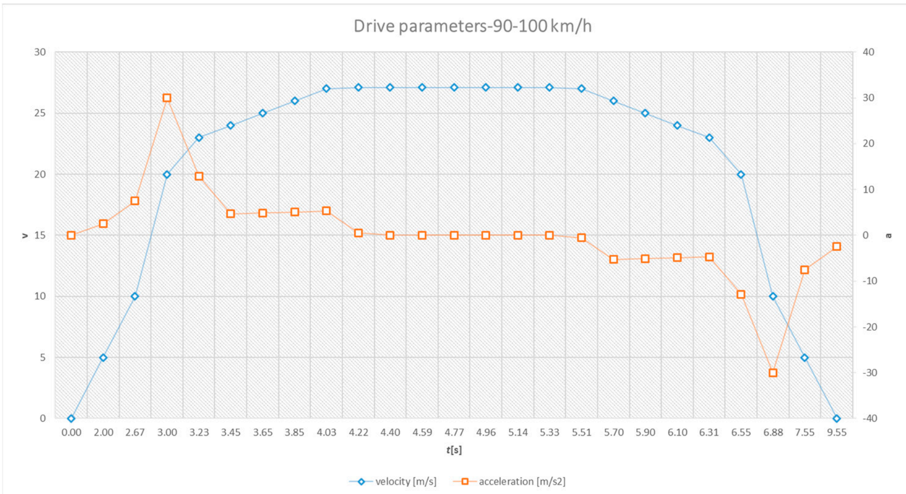
Option (1) is the most expensive of the compared variants. It turns out that it is an order of magnitude more expensive than the solution of propositions (2) and (3). By comparing variants (2) and (3), the cheapest acquisition and operating price of solution (2) is obtained.

As an example for the application of the **second concept**, the parameters of a passenger car from the above-described first concept with selected energy sources A-E can be considered. This car model will be considered only when driving on a road due to the simplicity of solving the moving Equation (2) with the consideration of the average smooth surface. The exemplary solution is based on the analysis of the dynamics of the modeled car's movement and the parameters described by the differential Equation (2). For example, the dynamics of speed, acceleration, and energy needed for starting and braking depend on the parameters of the model example. The graphically interpreted results of a simple solution to the dynamics of the selected vehicle model according to Equation (1) are shown in Figure 8. Vehicle starting/braking and flat driving with respect to friction for two scenarios were considered. The first one is shown with a maximum speed of v = 50–60 km/h achieved in Figure 8a. The second car dynamics model is solved for a maximum speed of v = 90–100 km/h, as show in Figure 8b. The considered choice of speed is based on the established road traffic rules in the village (v_{max} = 50–60 km/h) and outside the village (v_{max} = 90–100 km/h), as well as other traffic habits. For the case of covering the peak power P_p requirements (50%) from conventional energy sources (combustion engine) for starting and braking the car, the results are shown in Figure 9. For the maximum use of "alternative" sources (90%) and energy recuperation and accumulation, the parameters and solutions of the equation of the motion of the model are shown in Figure 10.

Figure 8. *Cont.*



(**a**)



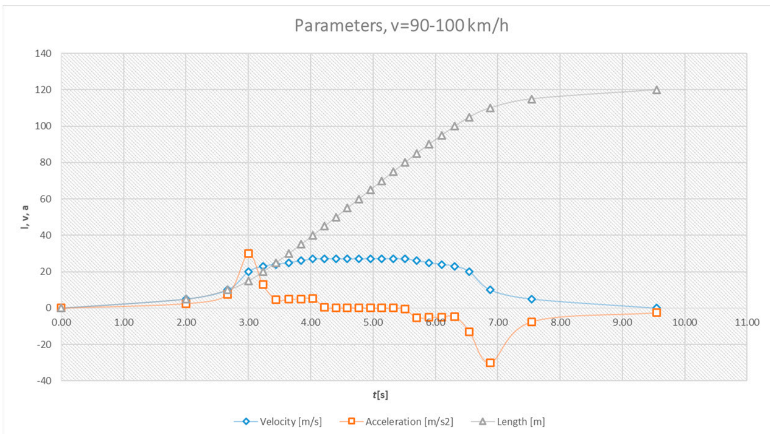
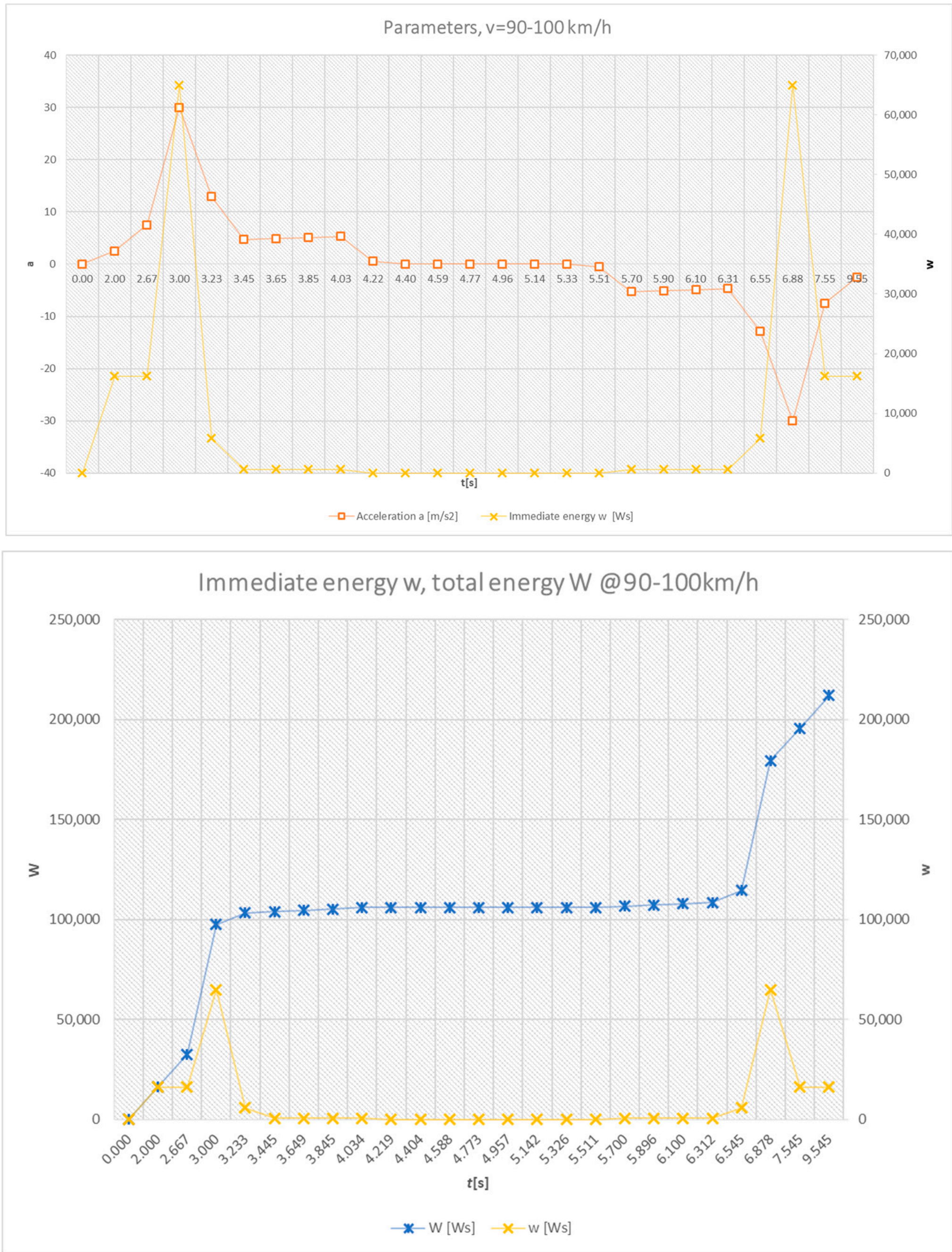
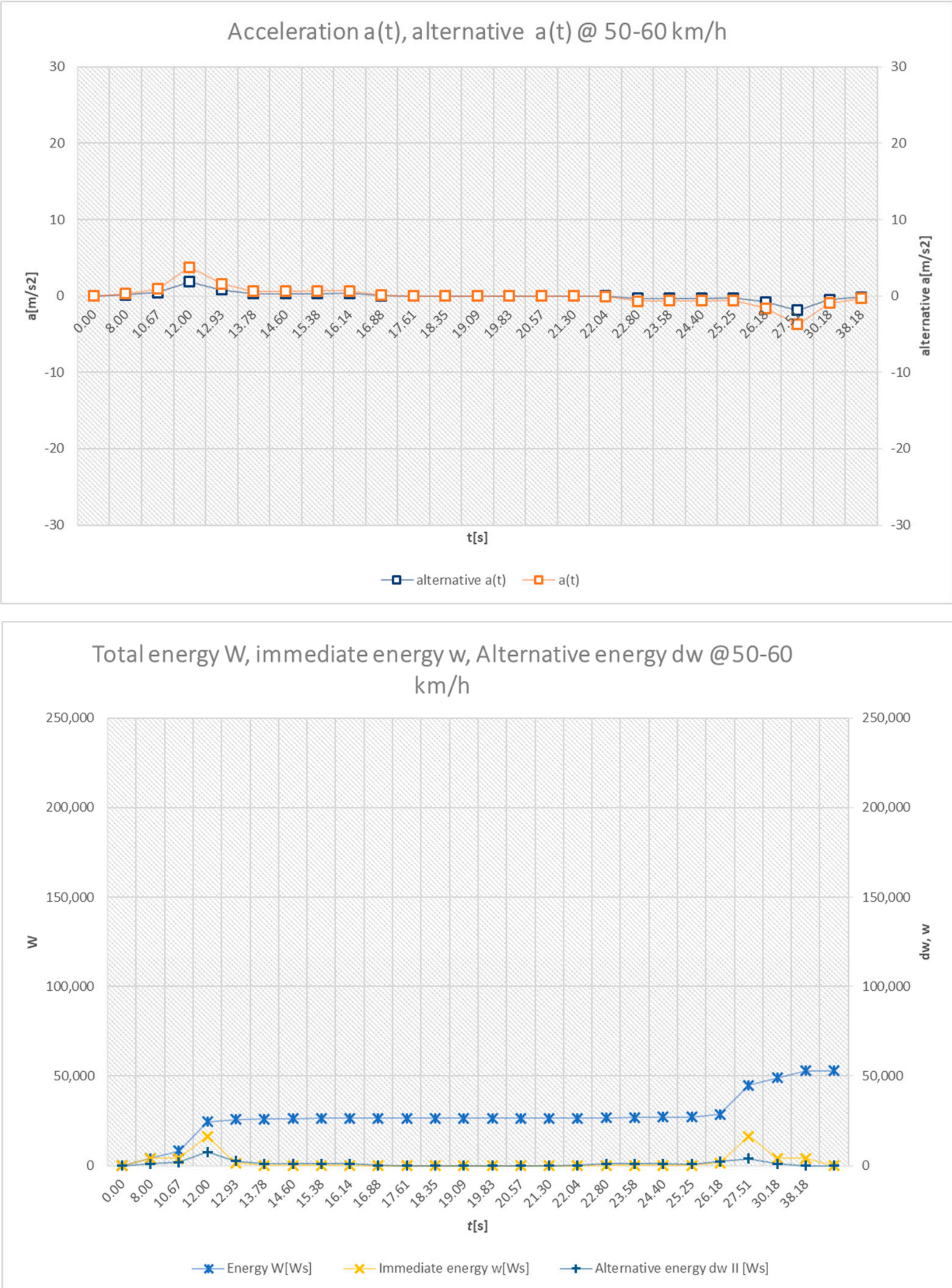


Figure 8. *Cont.*



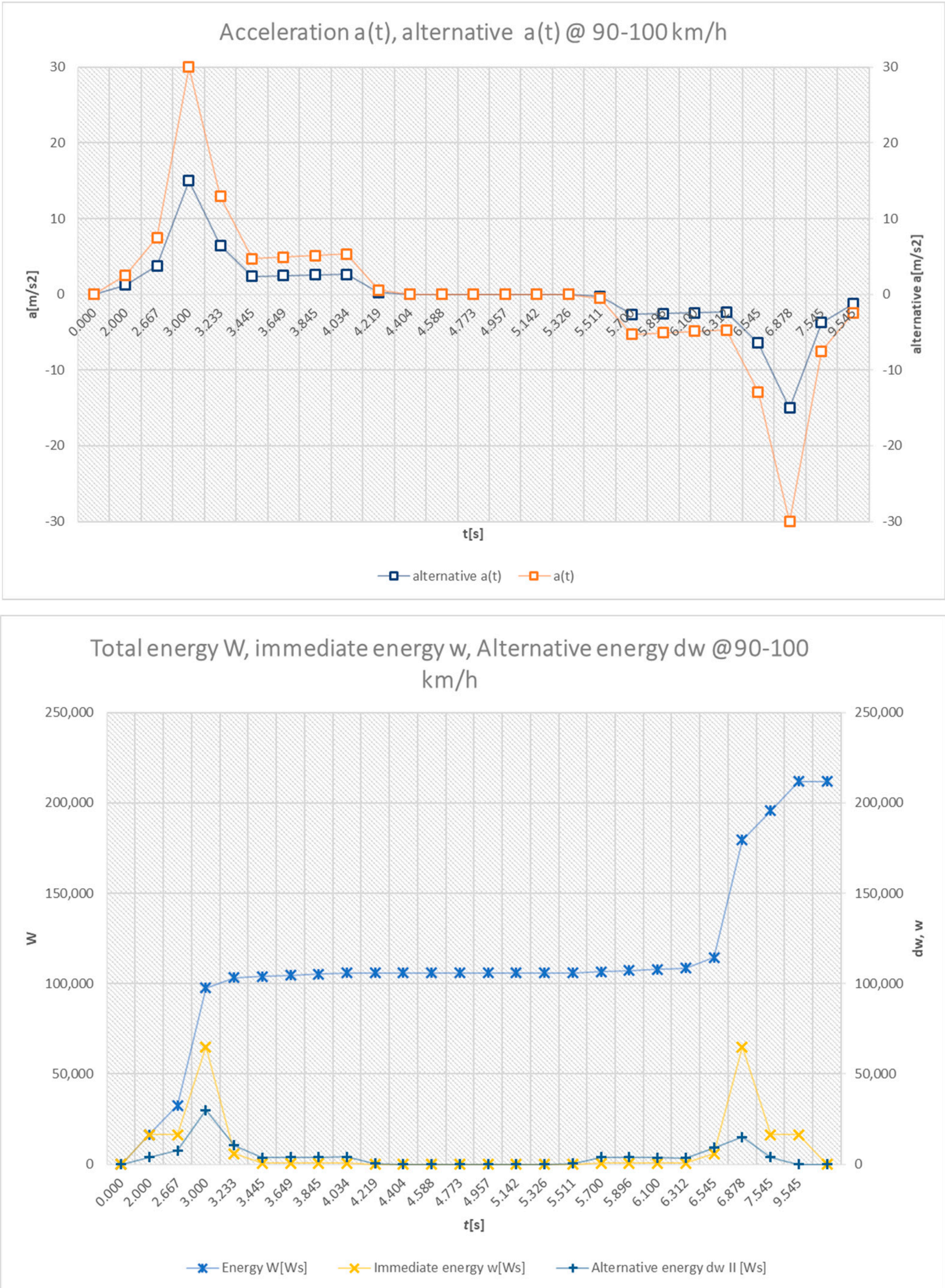
(**b**)

Figure 8. (**a**) The car movement parameters m = 1000 kg, straight section, start, braking, v_{max} = 50–60 km/h, basic movement dynamics. (**b**) The car movement parameters m = 1000 kg, straight section, start, braking, v_{max} = 90–100 km/h, basic movement dynamics.



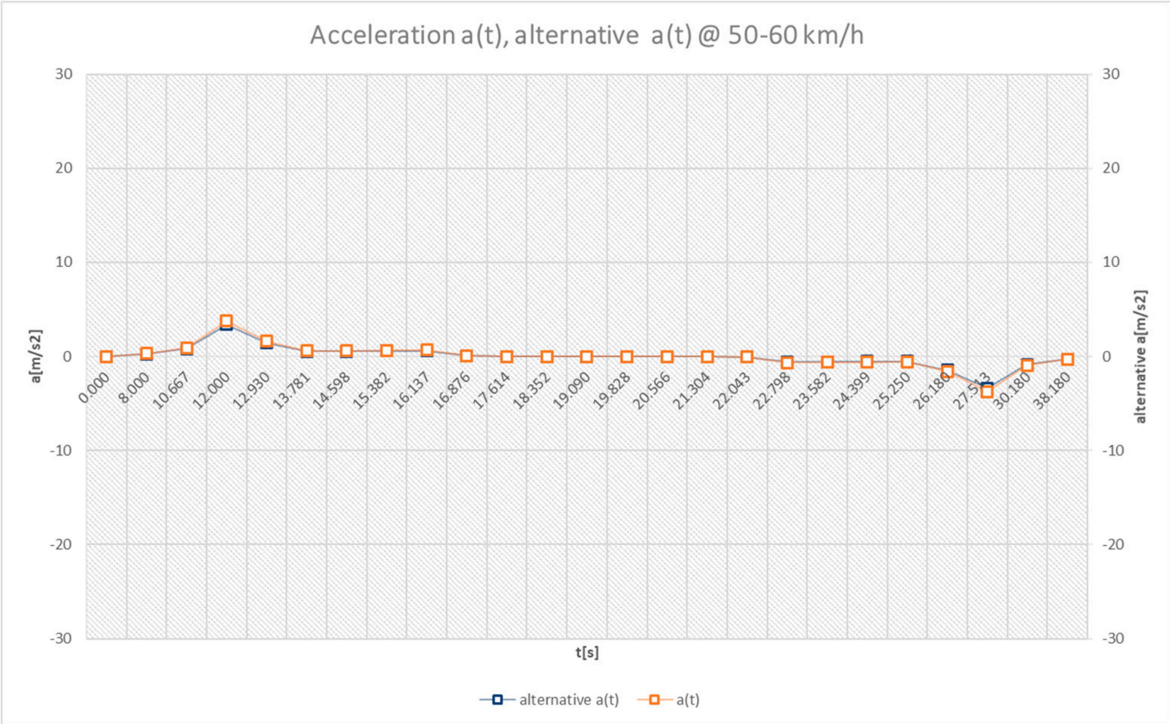
(**a**)

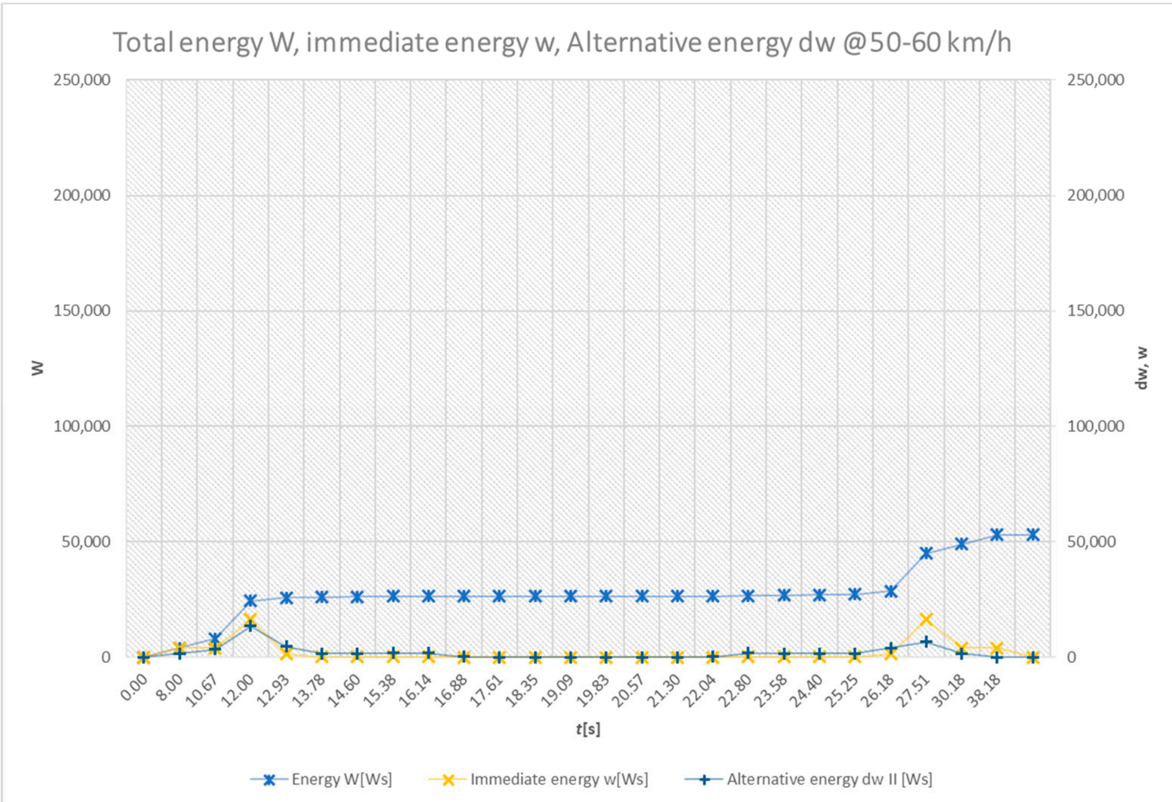
Figure 9. *Cont*.



(**b**)

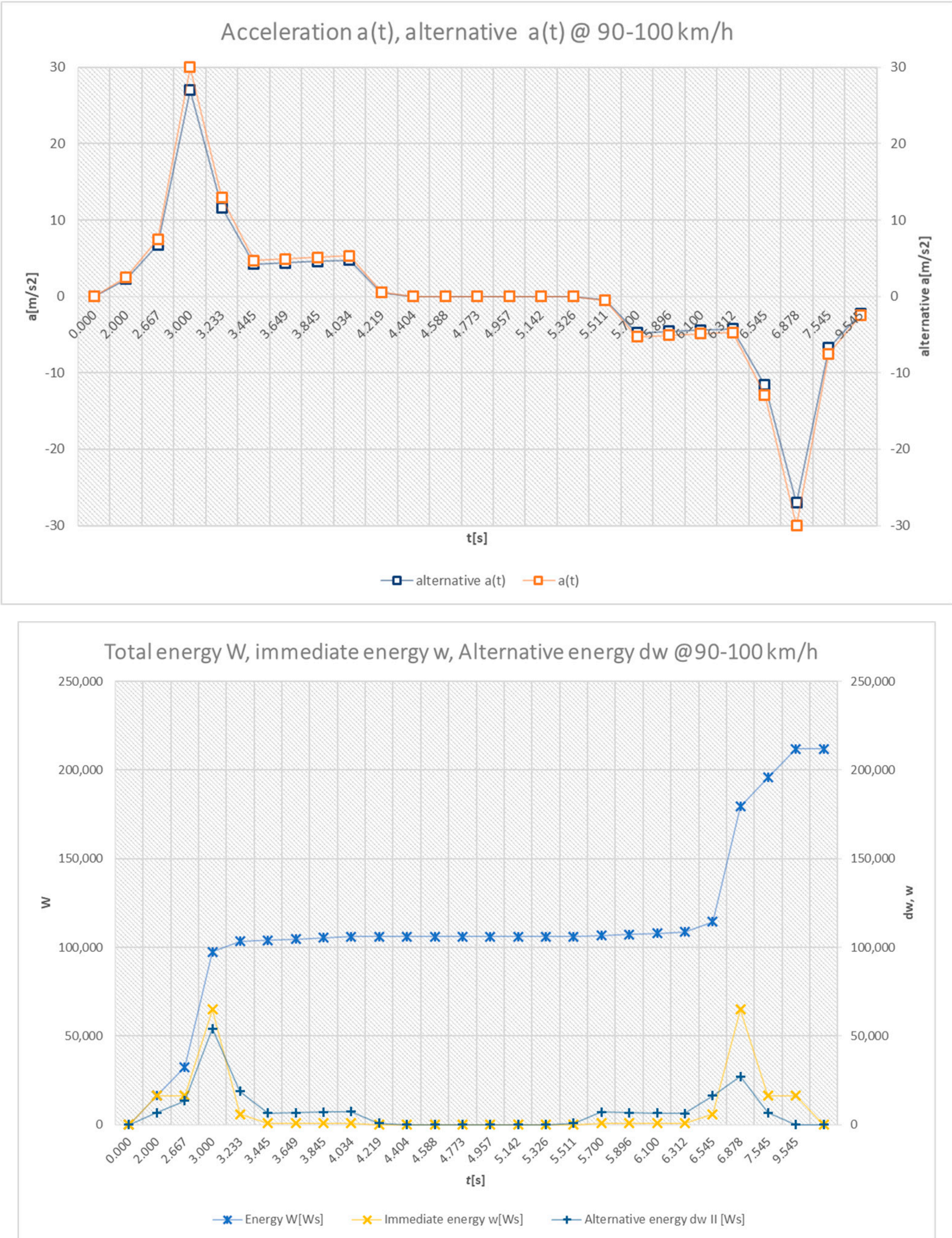
Figure 9. (**a**) The car movement parameters m = 1000 kg, straight section, start, braking, v_{max} = 50–60 km/h, combined forms of energy for movement dynamics, maximum use of alternative sources (50% of total consumption during starting/braking). (**b**) The car movement parameters m = 1000 kg, straight section, start, braking, v_{max} = 90–100 km/h, combined forms of energy for movement dynamics, maximum use of alternative sources (50% of total consumption during starting/braking).





(**a**)

Figure 10. *Cont*.



(**b**)

Figure 10. (**a**) The car movement parameters m = 1000 kg, straight section, start, braking, v_{max} = 50–60 km/h, combined forms of energy for movement dynamics, maximum use of alternative sources (90% of total consumption during starting/braking). (**b**) The car movement parameters m = 1000 kg, straight section, start, braking, v_{max} = 90–100 km/h, combined forms of energy for movement dynamics, maximum use of alternative sources (90% of total consumption during starting/braking).

When quantitatively evaluating the scenarios from Figures 8–10, it is easy to define the **second strategy** in the following way, which can be summarized in Table 2.

Table 2. The quantitative evaluation of the deployment scenarios of the modeled car's energy sources (basic dynamics, movement on a plane, m = 1000 kg).

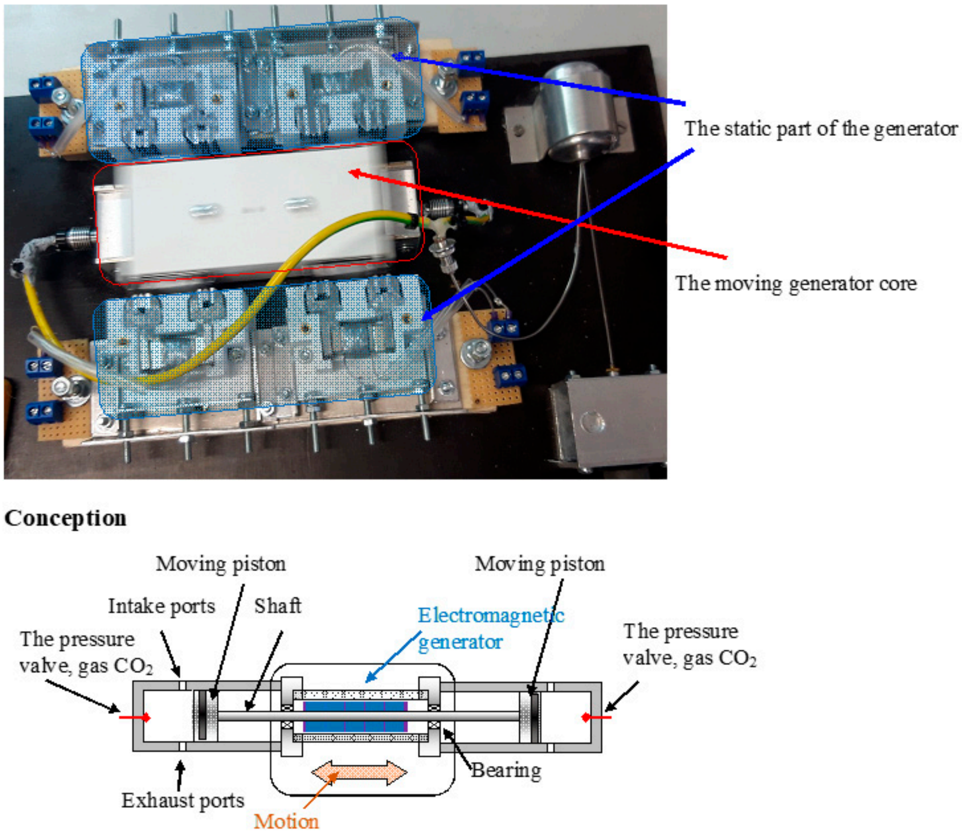
Energy Generation, Parameters	[1] $w_{start\text{-}stop}$ [Ws]	[2] w_{drive} [Ws]	[3] $W_{major,cum}$ [Ws]	[4] dw_{max} [Ws]
one energy source, v = 0–60 km/h	26,500	4.5	52,900	0
one energy source, v = 0–100 km/h	105,900	18	211,900	0
alternative energy source, 50%, v = 0–60 km/h	26,500	4.5	25,400	27,500
alternative energy source, 50%, v = 0–100 km/h	105,900	18	101,700	110,100
alternative energy source, 90%, v = 0–60 km/h	26,500	4.13	3400	49,500
alternative energy source, 90%, v = 0–100 km/h	105,900	16.5	13,600	198,300

[1] the energy needed to start the vehicle or brake. [2] the energy required to keep the vehicle moving. [3] the energy of the majority source of vehicle propulsion, cumulative consumption for the entire section. [4] the energy from alternative sources for immediate consumption or accumulation.

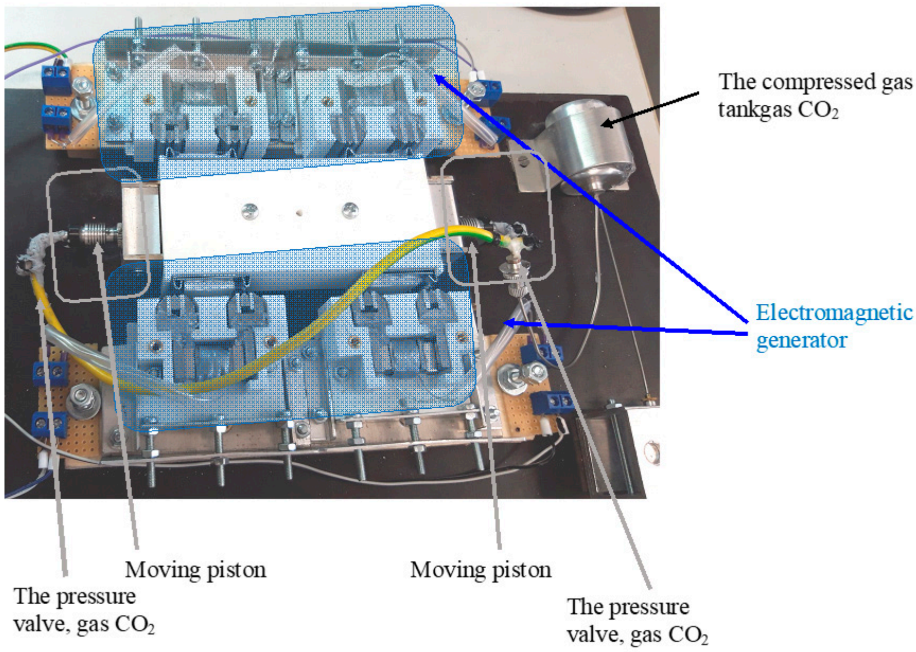
From Table 2, it can be easily demonstrated that the use of "alternative sources" (compressed air, electric battery, etc.), independent of the immediate presence of an energy source (sun, heat, organic fuel, etc., or sufficiently accumulated), can cover "consumption and requirements". The table shows the energy sources and their fulfilment; for example, a simple model task of starting a passenger car. The maximum achievable speed vmax and braking to a speed of v = 0 km/h is exemplarily determined in the model according to the dynamic movement of the mass point (2). For example, the acceleration to the maximum speed for the corresponding time t was modeled for v_{max} = 50–60 km/h and v_{max} = 90–100 km/h, as shown in Figures 8–10.

In the case of using only one major energy supply unit, the values of the constant energy consumption and the cumulative energy value are calculated in rows 1 and 2 of Table 2. If we consider the use of alternative sources of accumulated energy to cover approx. 50% of the consumption of the car model while driving, the values of the monitored variables in Table 2 on lines 3 and 4 correspond to this. These data are compared, and a simple conclusion can be drawn. The cumulative energy supply requirements from the main source will be reduced by the corresponding percentage released from other sources. On the other hand, it is necessary to have a reserve for the supply of unexpected energy peaks in real operation. When increasing the replacement of starting and driving energy from alternative energy sources to 90%, the decrease in the load on the majority energy source is again proportional to this percentage. From the dynamic data for the modeled case, it is easy to determine the maximum peak energy and power consumption; for v_{max} = 50–60 km/h, it is approximately $P_{max,60}$ = 53 kW, while to achieve a speed of v_{max} = 90–100 km/h while observing the acceleration parameters, etc., it is $P_{max,100}$ = 211 kW, as shown in Figures 10–13.

Another result of the analysis of the model example is the finding that the concept and performance of energy sources for a passenger car with driving characteristics requirements are close to the performance values of $P_{max,60}$ and $P_{max,100}$. However, a conventional internal combustion engine can operate inefficiently after starting. It is also a fact that the requirement for the energy supply to keep the vehicle moving is an order of magnitude lower than when it starts. However, the goal is to strive for highly efficient energy accumulation during vehicle braking. The principles of multiple energy storage methods therefore address the efficiency of vehicle energy consumption. It is then possible to effectively dimension individual sources while taking into account the parameters in Table 1. From this consideration, the peak power P_p of a common or alternative combustion unit can be reduced to the values $P_{max,60}$ = 4 kW and $P_{max,100}$ = 15 kW, as shown in Figures 10–13. With regard to the design of a possible energy source concept from Figures 6 and 7, the combustion unit can be set to optimal operation. This happens during constant "speeds". This will make the conversion and energy consumption more efficient for the realization of the required power consumption over time. If linear combustion units, shown in Figure 1, or units with conversion-to-rotational motion, shown in Figures 2 and 3, without inertial mass m_s were used, a significant increase in the effective use of the conversion of fuel energy into the movement of the modeled car can be expected [42].



(**a**)



(**b**)

Figure 11. Experimental cell of a linear electromagnetic generator, (**a**) movement in the active part of the linear generator, (**b**) arrangement of the basic element of the linear electromagnetic generator.

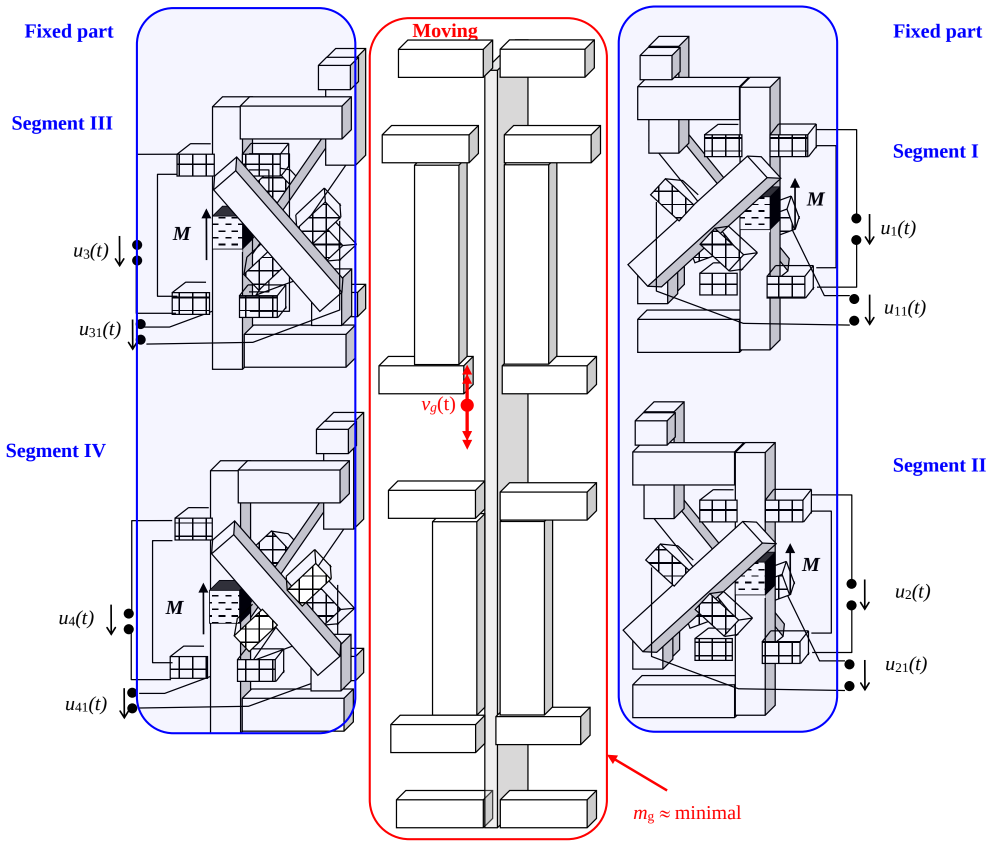


Figure 12. The concept of a cell of a linear electromagnetic generator, the basic dynamic parameters, the choice of construction, and the weight m_g of the moving part of the generator.

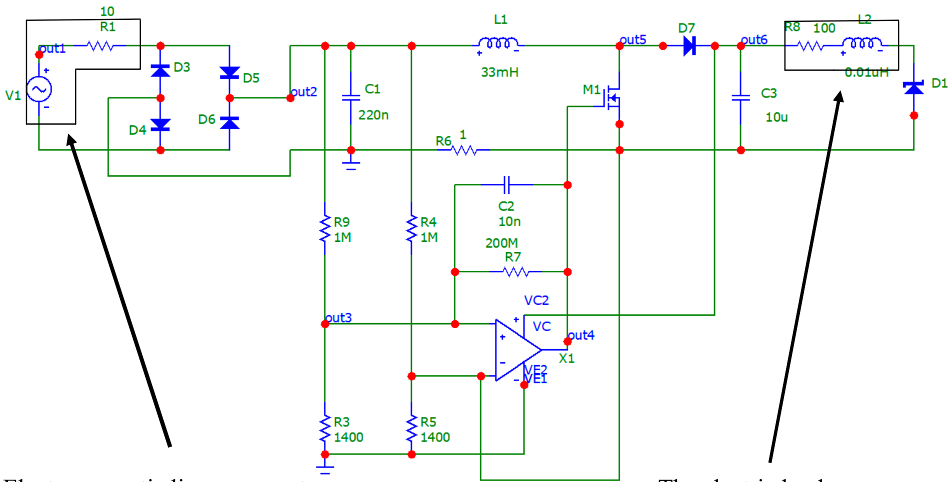


Figure 13. The generator power management circuit and PFC circuit for maximum conversion to output real power p.

5. Experiments

The authors have conceived and structured a magnetic circuit for a small displacement linear energy converter [25]. In the laboratory experiments, an equivalent motion source was employed. The unit was made ready for a testing cycle involving a gas-powered engine; presently, by extension, a CO_2 power unit was tested within the configuration, showing that the actual arrangement and structure in which generators are combined with engines embody a progressive and promising solution.

As an experimental test, a concept of an electric generator arrangement based on the principle of linear motion and achieving the minimum inertia mass mg requirement was proposed. The motor is driven by gas pressure. The proposed arrangement is shown in Figure 11a. The concept uses two piston drive units, shown in Figure 1c, driven in the laboratory version by compressed CO_2 gas. A CO_2 gas engine was assembled for the experiment, shown in Figure 11b. Theoretical parameters for the connection of the motion generator (CO_2 engine) and the electric generator with a description of the expected changes in the magnetic flux were published in study [25]. The concept of the experimental test was selected from previously published designs of an electromagnetic generator [25], as shown in Figure 12.

The windings of the coils with turns N_1, N_2, ... N_4 of the experimental generator, shown in Figures 11 and 12, are connected in series in one sense of the polarity of the output voltage. The output voltage from the generator is connected to the power control block. The basic element of this block is an electrical circuit operating on the principle of power factor correction (PFC), shown in Figure 13. In segments I, II, III, and IV of the experimental generator, shown in Figure 11, the number of turns of the coil was $N_1 = N_2 = N_3 = N_4 = 1000$ and the linear velocity of the moving part of the generator reached the value $v = 4$ m/s; the unit was driven by compressed CO_2 gas with a pressure $p = 100$ MPa and $m_g = 150$ g, corresponding to the model from Equations (2)–(11).

6. Conclusions

The concept of the selection and choice of alternative energy sources was presented on a model example of a passenger car. The analysis of the model showed the parameters that rationally enter into the process of the selection and design of the concept of usable energy sources with an emphasis on optimum energy consumption. This also depends on the amount of brake energy accumulation.

A simple example of evaluating the dynamics of a passenger car movement showed the possible ways of deploying generators and energy accumulators. For two driving modes parametrically corresponding starting and braking in an urban and suburb area, the influence of the choice of sources for an effective driving mode was shown. From this graphically documented example, it is clear that the starting and braking of a car is the most energy-intensive. It is therefore desirable to be able to accumulate braking energy as efficiently as possible for its following reusage.

A well-known method of storing energy in compressed air was designed as a simple and effective accumulator for such energy. Auxiliary sources such as a solar panel and a Peltier cell serve as additional power for slow energy accumulation. The example demonstrated the influence of the representation of alternative sources on the design, concept, and size of commonly used combustion engines. The text of the work brings a rational approach to the choice of principles and technical design solutions and the selection of energy sources that are suitable for powering non-stationary systems. The text reminds us of the neglected parameter that is useful for comparing of energy sources: the quantity of the power volume density corresponding to the technical design of the source or accumulator.

The concepts and structures involved in the presented model of a passenger car rely on a small-scale laboratory experiment with a compressed gas-powered linear generator. The approach delivers a power yield rate 2500 times higher than that achievable with the classic options for designing electromagnetic circuits [25].

This research report exposes selecting and combining suitable energy sources as major factors for the effective and environment-friendly use of natural resources. This goal, however, is preconditioned and practically illustrated through an optimum design of an electromagnetic linear generator that facilitates reducing the overall power consumption. Importantly in this context, the applied model solutions also expose the necessity to investigate and resolve energy accumulation, especially regarding the hitherto unused sources, with the aim to reduce the overall consumption via the recuperation of cogeneration. The repeated use of energy in laboratory experiments involving a linear generator to power a car under optimizable technical and consumption-related parameters is significant.

Author Contributions: P.F. and J.Z. contributed to the theoretical part, numerical modeling, and design of the experiments, and they also co-wrote the paper; Z.S., J.Z. and M.K. conceived and designed the experiments that allowed partial verification of the effects; and J.Z. modified the manuscript graphically and participated in evaluating the experiments. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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