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New Trends and Prospects for Developing Local Power Sources Based on Fuel Cells and Power Storage Units for Critical Infrastructure Customers

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Abstract: A reliable and efficient power supply for critical infrastructure customers is key to ensuring energy security. Critical infrastructure requires local power sources. Currently, performance requirements for such sources have significantly increased. Apart from high energy efficiency, important requirements include quick start-up time, small size, environmental friendliness, low noise, etc. These may be provided by fuel cells, which are considered the most prospective sources of electric power. However, it is necessary to overcome a number of obstacles limiting fuel cell efficiency in power supply systems for critical infrastructure customers. This paper presents the results of design analysis in the field of fuel cell, hydrogen conversion and power storage technologies. An assessment is given of promising studies aimed at combining the abovementioned technologies to create local power sources to ensure reliable power supply to critical infrastructure objects.

Keywords: critical infrastructure customers; proton-exchange membrane fuel cells; solid oxide fuel cells; hydrogen conversion; electrochemical power storage; redox flow batteries; energy security; energy efficiency; accumulator battery

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1. Introduction

The electrical power industry is inextricably linked with all spheres of life in modern society. Therefore, disruptions in the normal operation of power plants or electric grids affect the operation of industrial enterprises, electric transport, utilities, etc. Of particular importance are the so-called critical infrastructure objects, forming a combination of systems and means. Their failure can result in harmful consequences for the economy and population of a country [1]. Such infrastructure objects include [2–4]: industrial enterprises with a continuous production cycle; oil and gas production and processing plants; plants with a high penetration of digital technologies used in control systems, etc.

Natural phenomena, technical problems, as well as deliberate human actions may be classified as the main threats to the power sector [5]. It is impossible to ensure absolute protection of the electric power industry against the above-listed factors and influences. However, approaches to reduce the vulnerability of electric power objects are known and being developed in many countries.

The first approach is to build an energy system based on high-power sources operating on different physical principles of power generation: thermal power plants; nuclear power plants; hydraulic power plants; gas piston and gas turbine units; wind and solar power plants, etc. The major disadvantages of this approach are the following: substantial electric energy losses during transmission, frequent emergency shutdowns, and low-quality power supply to remote customers.

The second approach currently dominant in the world is the development of distributed generation, which involves electric power production in relative proximity to customers and the integration of distributed sources, energy storage units and consumers through a single control system [6]. Modern control systems designed for use in electric grids with distributed generation sources make it possible to ensure reliable power supply to customers even in case of failure of one or a group of sources [7].

However, the most vulnerable components of power supply systems are electrical networks and switchgears. These components are the most susceptible to atmospheric influences, short circuits, personnel errors, etc., [8].

Therefore, increasing the reliability of power supply to critical infrastructure facilities requires bundling in separate groups with the possibility of power supply from local power sources operating in the case of the complete absence of electricity from the external electric grid. At the same time, in modern conditions, requirements for power sources for critical infrastructure customers have significantly increased. This engenders the need to combine several related technologies to create such power sources.

This paper aims to provide an informed perspective and analysis of the problems and prospects of using fuel cells as local power sources for critical infrastructure customers. The contribution of the article is in the systematization of fuel cells, hydrogen conversion technologies, and power storage projects, as well as the justification of their combination when building local power sources for critical infrastructure customers.

The remainder of this paper is organized as follows. The concept of building and the requirements of local power sources for critical infrastructure customers is given in Section 2. Section 3 addresses the current state and challenges of using low-temperature and high-temperature fuel cells as power sources for critical infrastructure customers. Section 4 discusses prospective research trends in the field of fuel cells, as well as related technologies, the development of which is necessary to build efficient local power sources. Section 5 separately discusses the aspects of using various types of electric power storage as part of local fuel cell sources. The article concludes with Section 6, which summarizes the limitations of the use of fuel cells and strategies to overcome such limitations.

2. Design Principles and Requirements of Local Power Sources for Critical Infrastructure Customers

The principal requirements of modern power sources for critical infrastructure customers are:

- Ease of implementation and high reliability (including easy maintenance and recovery in case of failure);
- High efficiency;
- Increased installed capacity (with the possibility of increasing the installed capacity during operation);
- Quick start-up time;
- High maneuverability (wide range electricity production regulation in accordance with daily consumption schedule);
- High energy density;
- Small size.

For some customers, the more important requirements are environmental friendliness, low noise, and the possibility to increase the installed capacity during operation.

Figure 1 shows a flow chart of the structure of local power sources for critical infrastructure customers.

The brief characteristics of the flow chart components are presented below.

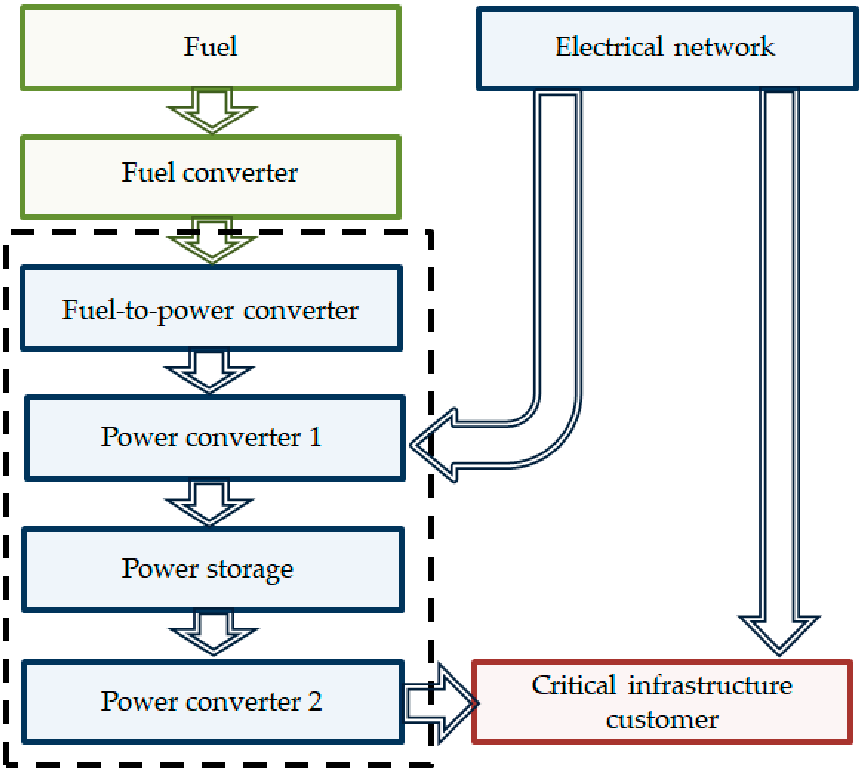

Figure 1. Structure of local power sources for critical infrastructure customers.

2.1. Fuel and Fuel Conversion

Usually, critical infrastructure customers have significant limitations and increased requirements relating to their location. This is due to:

- Being located in heavily built-up areas;
- Low throughput capacity or lack of utilities;
- Increased danger of damage, etc.

All of these factors influence the primary fuel requirements of local power sources. It is important that the fuel is not dangerous to the functioning of critical infrastructure customers. With this in mind, engine and gas engine fuels are most suitable. However, power plants using such fuels do not meet other requirements of local power sources (such as high efficiency and environmental friendliness).

Hydrogen is considered a promising fuel type. One method of hydrogen production is water electrolysis using renewable energy sources. This method helps solve renewable energy source problems, connected with temporal gaps between the availability of energy and its consumption by end-users [9].

Due to its low molecular weight and high molar combustion heat, hydrogen has an outstanding energy value on a unit mass basis. However, due to its low density, hydrogen's heating value per volume is significantly smaller than that of conventional fuels. Therefore, the problem with using hydrogen as a fuel lies in its storage. When storing hydrogen in large volumes, even a small leak can cause an explosion. Furthermore, hydrogen tends to diffuse through its storage material resulting in material embrittlement which can cause fires and explosions.

2.2. Conversion of Fuel to Electric Power

A key component of the flow chart is the fuel-to-power converter, which is a power source that runs on primary or converted fuel. Electric power plants based on petrol and diesel generator units, steam turbines and gas-turbine units have become very popular with low- and medium-power customers. High energy efficiency is the principal requirement for a power source to ensure the long-term autonomous operation of critical infrastructure customers (Figure 2) [10].

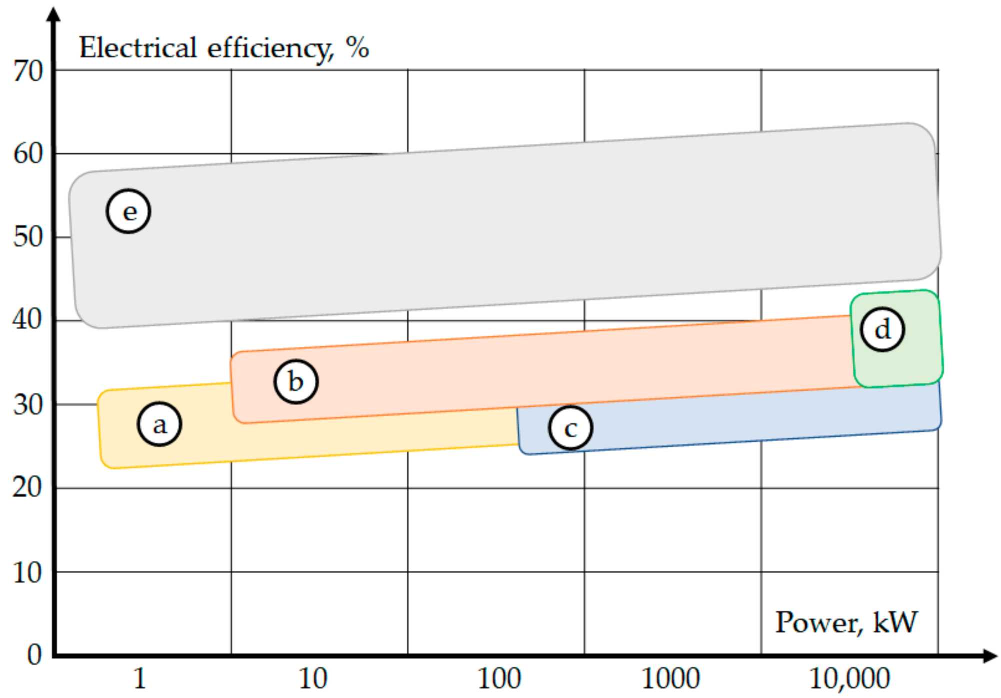

Figure 2. Electrical efficiency of power plants of various types: (**a**) based on petrol generator units; (**b**) based on diesel generator units; (**c**) based on steam turbines; (**d**) based on gas-turbine units; (**e**) based on fuel cells.

Currently, the most efficient power sources are fuel cells, with their electrical efficiency reaching 60% [11]. Furthermore, fuel cells meet almost all of the abovementioned requirements of local power sources for critical infrastructure. Compared to electric power sources based on hydrocarbon fuel, fuel cell operation is characterized by the absence of toxic combustion product emissions and vibrations and has a minimal noise impact. This is especially important for critical infrastructure customers with tough environmental requirements.

However, the efficient use of fuel cells in power supply systems to stationary customers demands a solution to a number of tasks that pertain to increasing the service life and combined use of fuel cells.

2.3. Electric Power Storage Systems

An important element of a local power source is its power storage system. The principles of implementation of a storage system may be different and depend on the type and capacity of its primary power source.

Thus, when using high-power fuel cells (over 100 kW) running on hydrogen, it is practical to use an electrolyzer (or a hydrogen generator) as a storage system. An electrolyzer allows for the use of excess power generated by a fuel cell to produce additional hydrogen [12]. However, this approach is not suitable for critical infrastructure customers, as it requires additional space.

Electrochemical electric storage devices (batteries) are more appropriate for critical infrastructure customers. Therefore, fuel cell capacity and its service life depend on the hydrogen storage volume. However, if the customer's power-consuming units operate in pulse modes, the fuel cell capacity may appear to be insufficient to cover peak loads. The additional usage of electrical energy stored in accumulator batteries (during the customer's low load or its absence) lowers the requirements for the installed capacity of the fuel cell.

Moreover, the use of batteries allows for:

- Efficient operation mode of fuel cells;
- Uninterrupted power supply to customers in case of dynamic load changes.

Thus, accumulator batteries can be considered not only as a buffer but also as a booster for the whole local source. Hence, accumulator battery capacity can manifold exceed that of the fuel cell, allowing for the expansion of a source's application area. However, an important task herewith is to improve the characteristics of power storage units in accordance with the requirements of local power sources for critical infrastructure customers.

2.4. Electric Power Converters

Electric power converters perform the function of matching power source parameters with those of the electric power storage (Converter 1 in Figure 1) and customer parameters (Converter 2 in Figure 1).

Series-produced DC-DC and DC-AC converters, which operate according to well-known algorithms, can be used in local power sources for critical infrastructure customers. However, depending on individual customers' needs, there may be differences in the types of connection between the power source and power storage, as well as in the algorithms of storage charging and power output. At the same time, the use of more complex types of connection (with a large number of sensors, calculations and control modules) provides more flexible control over the operating modes of a local power source. However, it must be borne in mind that the operation of power converters causes energy losses and requires the implementation of complex control strategies. The operation of power converters also results in current harmonics, which may accelerate fuel cell aging [13].

3. Local Fuel Cell-Based Power Sources for Critical Infrastructure Customers: Current Status and Issues

Currently, five types of fuel cells are most widely used [14–17]:

- Polymer proton-exchange membrane fuel cell (PEMFC);
- Alkaline fuel cell (AFC);
- Phosphoric acid fuel cell (PAFC);
- Molten carbonate fuel cell (MCFC);
- Solid oxide fuel cell (SOFC).

Fuel cells differ in the types of their components (electrolyte, electrode material) and operating parameters, which, first of all, include efficiency, operating temperature and service life.

3.1. Comparative Characteristics of Fuel Cells

Figure 3 shows the comparative characteristics of different types of fuel cells.

All types of fuel cells are characterized by a high efficiency of power generation, which is one of their main advantages over traditional power plants. However, the service life of various types of fuel cells can differ significantly (5 to 65 thousand hours). At the same time, the service life of fuel cells of one type may vary over a wide range, which is one of the problems with their use. Fuel cells are classified as per their operating temperature into low temperature (PEMFC, AFC, PAFC) and high temperature (MCFC, SOFC). The requirements for the quality of fuel used by fuel cells depend on the operating temperature. Therefore, the operating temperature, as well as the operational features of various fuel cells, must be taken into consideration when assessing the possibility of using them as local sources for critical infrastructure customers.

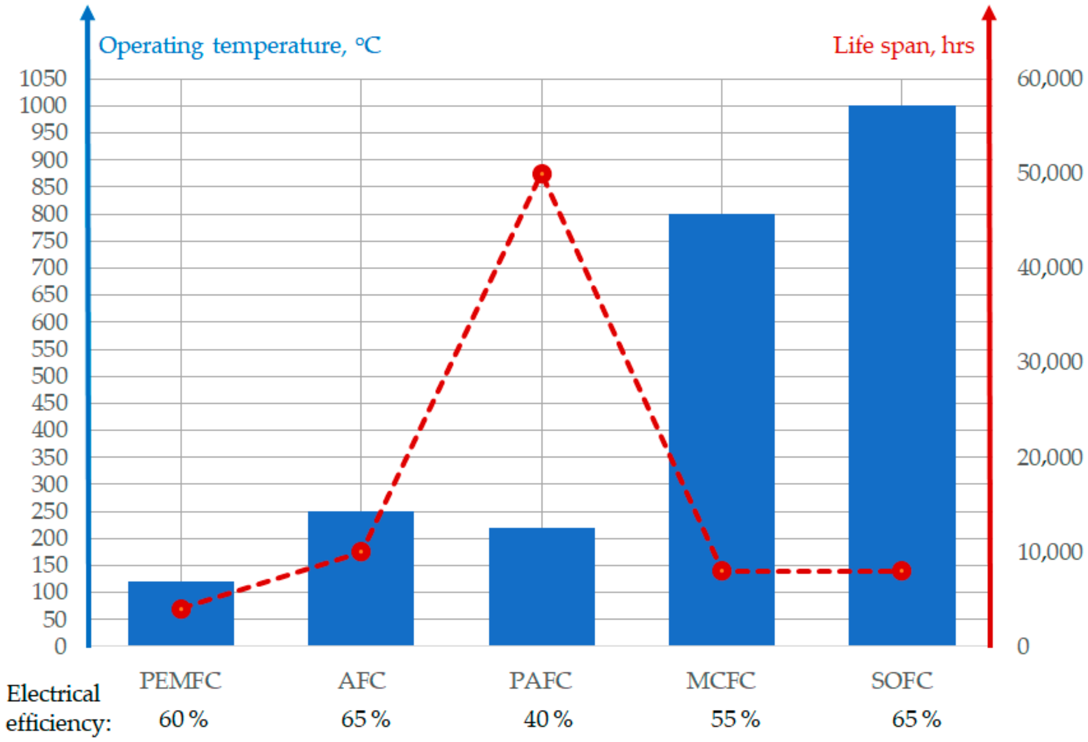

Figure 3. Comparative characteristics of fuel cells of various types.

3.2. Local Power Sources Based on Low-Temperature Fuel Cells

PEMFC has become a widely used type of low-temperature fuel cell. Their use as power sources for various types of vehicles [18–20] is being actively developed. This is due to their relatively low inertia and ability to quickly reach operating parameters [21]. PEMFC can also be used as a power supply source for stationary objects with a capacity ranging from several kW to several MW. For instance, research teams conduct studies on the use of PEMFC as power sources for remote settlements [22], water supply systems [23], etc.

However, a significant disadvantage of PEMFCs as a power source for critical infrastructure customers is the necessity to use pure hydrogen fuel [21]. The high requirements for the quality of fuel call for setting up the appropriate infrastructure for fuel preparation and storage.

Consequently, at the moment, local energy sources based on PEMFCs are prospective for powering critical infrastructure customers, the process cycle of which is related to the production of hydrogen. Typical examples of such customers are oil and gas enterprises. An expansion of the list of types of critical infrastructure facilities using PEMFCs, among other things, requires the development of hydrogen storage and conversion technologies.

Besides PEMFCs, AFCs and PAFCs also belong to the low-temperature fuel cell category. The AFC's major advantages are analogous to those of PEMFCs. The AFC's disadvantage is its high sensitivity to CO_2, which reacts with electrolytes and lowers fuel cell efficiency. CO_2 can be contained in the air; thus, AFC usage is limited to enclosed spaces (outer space environment, submarines).

The PAFC's major advantages are their relative simplicity of design, electrolyte low volatile grade and high stability. Consequently, the PAFC's service life has been estimated to be over 50,000 h. However, the PAFC's electrical efficiency is only about 40% which is lower than that of other fuel cell types.

3.3. Local Power Sources Based on High-Temperature Fuel Cells

High-temperature SOFCs are less demanding for fuel quality [24]. Due to high operating temperatures (up to 1000 °C), SOFC are able to use various types of hydrogen-containing fuels, such as methane, propane-butane, diesel fuel, etc. Therefore, local power sources based on SOFCs are prospective for use in power supply systems of critical infrastructure customers, which can produce hydrogen-containing fuels from industrial waste. Examples of such customers are agricultural enterprises (livestock and crop production), waste processing plants (treatment facilities), etc., [25]. Herewith, the heat obtained from SOFCs could be used in industrial heat supply systems or biogas generation systems by heat-exchange units.

The DEMOSOFC project has proven the technical and economic feasibility of using SOFCs [26]. Within the framework of this project, three SOFC modules of 58 kW each were used to power the wastewater treatment plant. The fuel used was biogas produced locally by anaerobic digestion of the wastewater sludge.

The main problem with the use of SOFCs is their low maneuverability [27]. This reduces the efficiency of the use of SOFCs in the case of frequent start-ups and shutdowns of SOFC-based power plants (for example, during periods of biogas unavailability). The solution to this problem lies in the use and development of power storage systems to maintain the high power factor of the SOFC (at low loads, SOFC generation surplus can come into the power storage system to be subsequently used during higher loads or peak hours).

The MCFC is another type of high-temperature fuel cell. MCFCs have relatively high electrical efficiency (up to 55–60%) and, like SOFCs, are tolerant to hydrogen purity (i.e., catalysts are not susceptible to CO and CO_2 intoxication). The MCFC's major disadvantages are the following: a short service life due to components' destruction and corrosion and slow start-up time. MCFCs are commonly used in medium-large scale combined heat and power systems of up to MW capacity [17].

4. Local Power Sources for Critical Fuel Cell Infrastructure Customers: Related Technologies and Prospective Solutions

The following main directions for the development of local power sources based on fuel cells can be distinguished by analyzing local power source structures for critical infrastructure customers (Figure 1) and the design and operation features of PEMFCs and SOFCs:

- Development of hydrogen storage and conversion technologies;
- Increasing operation life of fuel cells;
- Increasing parallel operation of several fuel cells efficiency;
- Development of power storage technologies.

4.1. Development of Hydrogen Storage Technologies

There are several approaches to solving the problem of hydrogen storage for critical infrastructure customers.

Currently, hydrogen compression technologies are widely used [28]. However, this approach is least suitable for critical infrastructure power supply systems. For instance, hydrogen compression in cylinders does not provide the high energy density necessary for the long-term operation of customers. The use of high-pressure cryogenic systems is not safe enough. Furthermore, the long-term storage of hydrogen causes brittleness in metals, limiting the possibility of their use.

For critical infrastructure customers, it seems more practical to store hydrogen in small volumes, which, while being safe, ensures the possibility of long-term functioning of the customer. Such hydrogen storage methods use metal hydrides and ammonia.

The replacement of traditional methods of storage and the use of metal hydrides lead to a dramatic decrease in storage system pressure. The research and development of new types of metal hydrides that are cheaper, cyclically stable, non-toxic, regenerable, and, most importantly, have a high mass concentration of stored hydrogen [29] are regarded as priorities.

Ammonia is a stable fuel that can be converted to hydrogen. Compared to hydrogen storage systems, the advantages of ammonia storage systems include lower storage costs and higher volumetric density [30]. The important task here is to increase the energy efficiency of the ammonia-to-hydrogen conversion.

Direct ammonia fuel cells (DAFC) may also be considered an alternative to hydrogen fuel cells. Compared to PEMFCs, DAFCs eliminate the step of ammonia-to-hydrogen conversion. However, the integration of such fuel cells into power supply systems requires additional research [31].

It is more practical to use biogas as fuel for local power sources based on SOFCs as it is safer than hydrogen.

4.2. Increasing Fuel Cells' Service Life

One of the reasons for decreasing the possible service life of fuel cells on a large scale is related to the inevitable processes of degradation of the membrane-electrode assembly (MEA) [32,33].

The main causes and effects of the degradation are shown in Figure 4 [34].

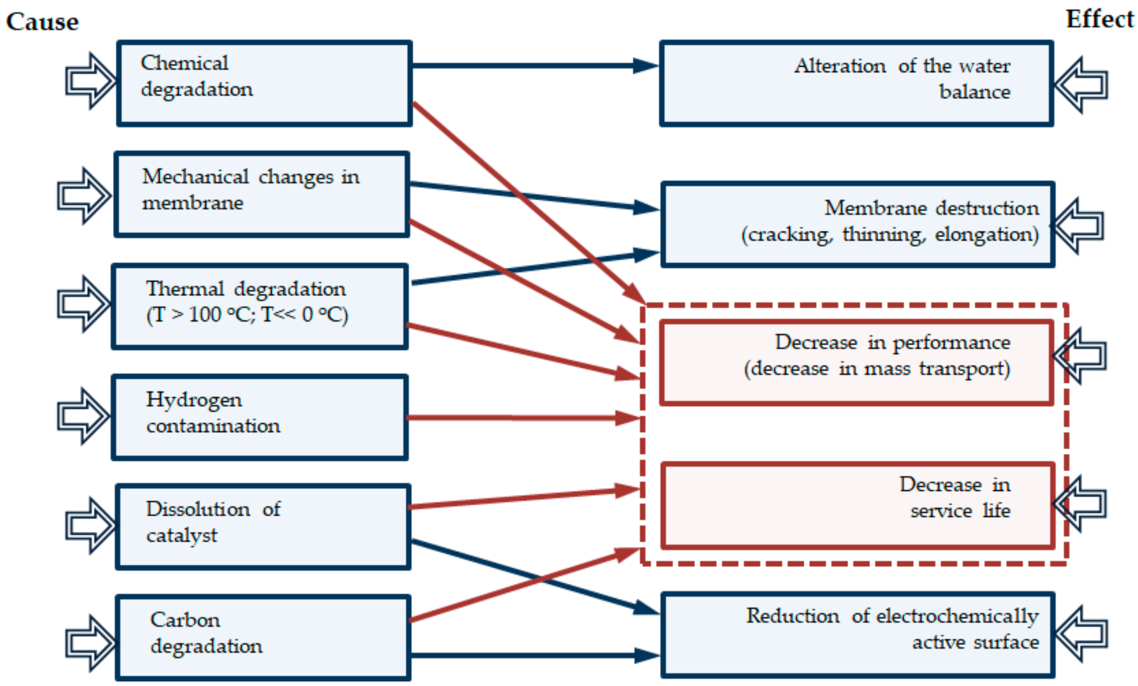

Figure 4. Causes and effects of fuel cell degradation.

Hydrogen-to-water oxidation and carbon degradation have the greatest impact on the operating parameters and life of PEMFCs since these processes take place in all fuel cell operation modes. It should be noted that the degradation of one MEA element leads to changes in the function of other parts of the PEMFC. Therefore, in operating conditions, it is quite difficult to determine the reason for the fuel cells' service life decrease.

Important areas of research in the field of increasing fuel cell life are related to the improvement of materials for MEA components and the development of methods to determine the degree of MEA degradation during operation [35–37].

However, it is impossible to completely eliminate degradation processes. Therefore, in order to reduce the rate and effects of degradation, special methods of influencing the MEA are being studied and developed [38]. Such methods include fuel cell activation with direct current, fuel cell activation with a high current pulse, fuel cell activation through voltage control, supply of hydrogen and nitrogen to the anode and cathode, and controlled cathode starvation.

Notwithstanding the results obtained, there is currently no unified view on the processes affecting the extent and time of MEA degradation. Any breakthrough solutions require a systematization of the results and larger studies in this direction.

4.3. Modular Use of Local Fuel Cell Sources

The modular use of local power sources involves the solution of two problems:

- Interfacing parameters of fuel cell and power storage devices into one module;
- Efficient combined use of multiple modules to power one customer.

Typical electric power converters can be used for the solution of the former. Herewith, series and parallel connections of the fuel cell and power storage devices are singled out (Figure 5) [17].

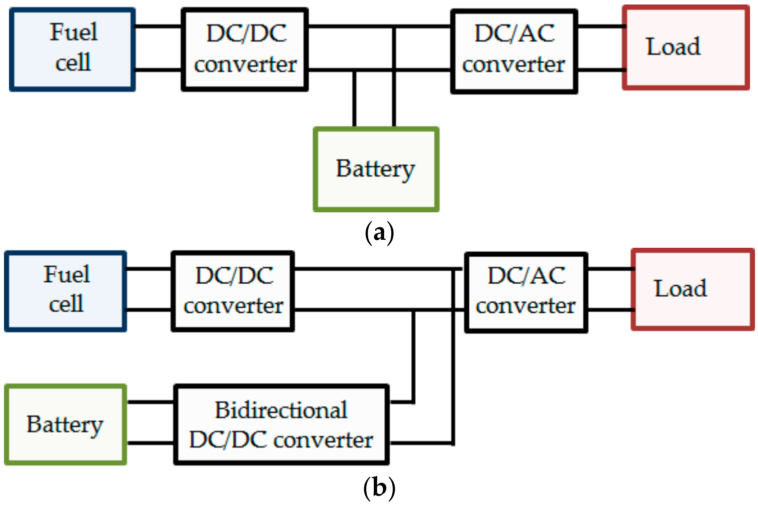

Figure 5. Interfacing fuel cell and power storage parameters: (**a**) series; (**b**) parallel.

The series connection uses only one converter between the fuel cell and the power storage. This scheme is simpler (may reduce energy losses, mass, and the complexity of the system), but it is important to determine the components' optimal parameters at the design stage. The parallel scheme includes an additional converter. The advantage of the parallel scheme is that the fuel cell can be operated with high efficiency. This scheme makes it possible to regulate each component's operation independently and, therefore, to avoid the fuel cell's adverse operating modes, for example, long operation at high cell voltage. The battery also protects the fuel cell by providing rapid variations of power to the load, which damages the fuel cell if its auxiliaries are too slow to respond. Supercapacitors can also be used to compensate for load pulses (for example, when starting electric receivers) in both schemes.

The selection of the serial or parallel connection, storage charging and power supply load algorithms is determined by individual customer characteristics.

For the purpose of their combined use in one power supply system, local power source modules can be combined by AC or DC. Given the requirements of critical infrastructure customers, it is more practical to combine AC modules. In this case, the failure of one component in a module (for example, an inverter) will not lead to the termination of the power supply. Furthermore, solving the problem of interfacing output parameters of DC modules will require the use of additional converters to equalize the output voltage levels.

5. Electric Power Storage as Part of Local Power Sources Based on Fuel Cells

5.1. Electrochemical Power Storage Units

Lithium batteries, which are characterized by a high energy density and minimal self-discharge index, have become the most widespread among electrochemical electric power storage units [39–41]. Depending on the cathode and electrolyte materials, several types of lithium batteries are distinguished (Table 1) [21].

Table 1. Parameters of lithium battery cells.

Type	Li-Ion	$LiFePO_4$		LTO	
Type (Form Factor)	**Cylindrical**	**Cylindrical**	**Prismatic**	**Cylindrical**	**Prismatic**
Capacity, Ah	0.7 ... 7	1.1 ... 50	10 ... 280	1.3 ... 40	2.9 ... 23
Gravimetric energy density, Wh/kg	120 ... 270	80 ... 140	110 ... 165	70 ... 96	46 ... 90
Voltage, V	3.6	3.2	3.2	2.4	2.3 ... 2.4
Charging current, standard	0.5C	0.5C	0.5C	0.5C	1.0C
Charging current, maximum	1.0C	1.0C	1.0C	5.0C	4.0C
Discharge current, long-term	2.0C	1.0 ... 3.0C	1.0 ... 3.0C	1.0 ... 5.0C	1.0 ... 3.0C
Discharge current, maximum	3.0C	3.0 ... 5.0C	3.0 ... 5.0C	5.0 ... 10.0C	4.0 ... 10.0C
Life, cycles, not less than	1000	2000	3500	10.000	15.000
Depth of charge–discharge, %SOC	20 ... 80	20 ... 80	20 ... 80	0 ... 100	0 ... 100
Operation temperature (discharge), °C	−20 ... +60	−20 ... +60	−20 ... +55	−30 ... .+60	−30 ... .+60
Unit value, $/Ah	1.0 ... 2.5	0.7 ... 3.0	0.5 ... 0.9	0.75 ... 3.0	1.0 ... 2.1

Lithium-ion batteries (Li-Ion) include $LiNiMnCoO_2$ (INR/NMC), $LiCoO_2$ (ICR/LCO), $LiMn_2O_4$ (IMR/LMO) and $LiNiCoAlO_2$ (NCA). This type of battery provides a large capacity, high specific energy and uninterrupted operation. However, the operation of Li-Ion batteries is affected by low temperatures, recharge and deep discharge [42].

Lithium-iron-phosphate ($LiFePO_4$) batteries are characterized by a long service life (10 times longer than Li-Ion batteries), high current output and high efficiency (up to 95%) [43]. This type of battery is the safest since it is characterized by thermal and chemical stability (i.e., the batteries do not ignite and are not toxic). However, charging $LiFePO_4$ batteries is allowed only at positive temperatures.

The advantages of lithium-titanate (LTO) batteries are a large service life (up to 20,000 cycles), complete discharge possibility and operation at negative temperatures [44]. In addition, LTO batteries withstand vibrations and do not provoke fire. However, this type of battery is characterized by low storage density and high unit value.

The operation of lithium batteries has a number of features [45,46]:

1. Aging. Unlike other rechargeable batteries, the Li-Ion batteries capacity declines slowly, which is related to the frequency of use and temperature. As it is related to temperature, it is easier for electronic products with a high working current to reflect.

2. Recovery rate. About 1% of new products need to be recycled for various reasons.

3. Overcharge intolerance. When overcharged, the excessive embedded lithium ions will be permanently fixed in the lattice and can no longer be released, which may lead to a short battery life.

4. Inability to over-discharge. During over-discharge, the electrode will be de-embedded with too many lithium ions, which may lead to lattice collapse, thus shortening the service life.

5. The technology used in the long-term energy storage scenario is still immature. Under adverse conditions, such as high temperature, absence of ventilation, large current, etc., the battery may explode or catch fire; a large number of mobile battery explosions have already been recorded.

Thus, there is no single optimal type of battery for a power storage system as part of a local power source for critical infrastructure customers. The existing battery types have disadvantages that conflict with the requirements of local power sources for critical infrastructure.

5.2. Flow Batteries

One of the most prospective and advanced technologies for the development of electric power storage is flow batteries [47].

Flow batteries include the vanadium redox flow battery (VRB). The VRB is an electrochemical cell in which vanadium ions in various oxidation states are used as charge carriers. Figure 6 shows a diagram explaining the principle of flow battery operation [48].

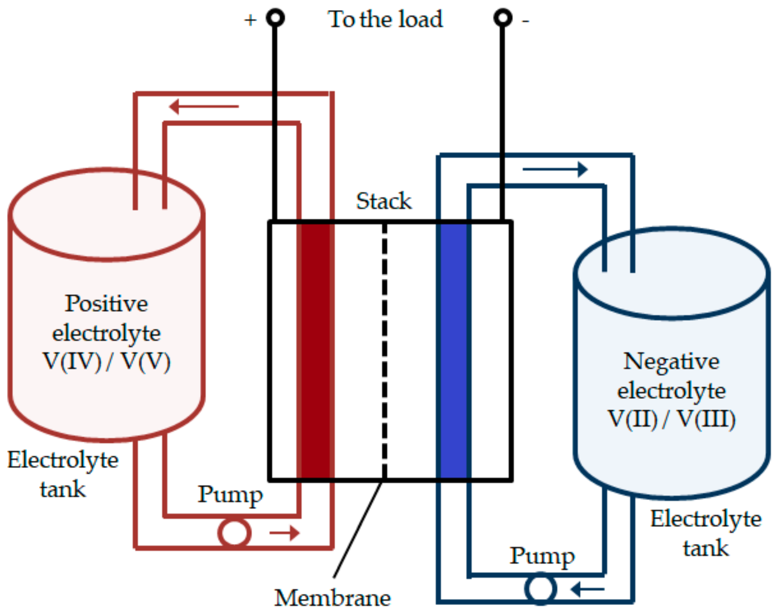

Figure 6. VRB electrochemical cell.

The key element of the flow battery is the flow cell (stack). The flow cell consists of two porous graphite electrodes separated by an ion-exchange membrane. Positive and negative electrolytes are passed through the electrodes. Apart from the cell, a flow battery includes a hydrodynamic system consisting of two tanks with positive and negative electrolytes pumped by pumps at a controlled speed.

Among other flow battery types, the most widespread one is the vanadium redox flow battery [49]. The use of vanadium ions in both electrolyte tanks eliminates the problem of cross-contamination, which is present in other technologies [50]. At the same time, the VRB use cation exchange membranes, and most of them, especially the commercial Nafion membrane, have very low ion selectivity between protons and vanadium species, and it does not act as an efficient barrier layer to vanadium species, which are the key materials for the solutions of vanadium flow batteries [51]. Therefore, vanadium ions can also permeate through the membrane and cause a crossover/self-discharge phenomenon, which reduces the battery capacity and energy efficiency. Three generations of vanadium batteries have been developed until now. They differ in the composition of electrolytes, as well as combinations based on Fe and V ions, and include the vanadium oxygen fuel cell (VOFC) and vanadium hydrogen fuel cell (VHFC).

In addition to the VRB, the best-known flow batteries are iron/chromium redox (Fe/Cr), polysulfide bromine (PSB), zinc-bromine (Zn/Br), zinc-chlorine (Zn/Cl), titanium-manganese (Ti/Mn) and hydrogen-manganese (H/Mn) [52]. Promising types of flow batteries include cost-effective zinc- and iron-based flow batteries due to the high cost of vanadium [53]. In comparison to lithium batteries (and other types of electrochemical batteries, such as lead–acid, gel cell, etc.), flow batteries are less subject to self-discharge and are able to store a full charge for a long period of time.

Flow batteries meet most local power storage requirements for critical infrastructure facilities:

- High efficiency (up to 75%);
- Long service life (four times longer than lithium-ion batteries);
- Operational in a wide temperature range (from −30 to +60 °C);
- Environmental friendliness;
- Fire and explosion safety.

Flow batteries designed for the accumulation of large amounts of electricity can be used indoors. In this case, output power (depending on the surface area of the electrodes) and the system capacity (depending on the volume of electrolyte) can be selected and increased during operation, taking into account the requirements of individual customers. The disadvantages of flow batteries are their low power, volumetric energy density and large electrolyte tank dimensions [54]. In addition, the complex design of a hydrodynamic system that requires periodic maintenance reduces local power source reliability.

However, despite the shortcomings, flow batteries are a promising technology for storing electricity in local fuel cell-based sources for critical infrastructure customers. Although flow batteries can take up more space than electrolyzers, their efficiency is higher.

LTO and VRB are efficient electrochemical power storage systems and, in many ways, have similar advantages and disadvantages. However, their application area is different because VRB-based systems have larger dimensions and can be used for long-term energy storage. They are more suitable for high-capacity stationary power storage systems, while modern LTO cells have smaller dimensions, higher energy density and high current overload capacity (discharge current of up to 10C), making it possible to use them as power storage systems for stand-alone devices. It should be also noted that LTO cells have a smaller unit capacity and lower voltage. Thus, in order to increase the system capacity, it is necessary to increase the number of cells, whereas VRB capacity can be boosted by increasing the volume of electrolytes in storage reservoirs.

6. Conclusions

To ensure a reliable power supply to critical infrastructure customers, local power sources are used, which operate even in conditions of complete absence of electricity from an external electric grid. In modern conditions, local power sources must comply with a broad list of requirements: high efficiency, easy use, quick start-up time, high maneuverability, small size, low noise, etc.

The most prospective sources that meet most of the requirements are fuel cells. However, the use of fuel cells is restricted by a number of technical limitations related to fuel storage (hydrogen), increasing storage system efficiency, and the required long service life.

Based on the analysis of relevant advanced designs, this paper presented the authors' approach to a possible combination of technologies for building local power sources that provide a reliable power supply to critical infrastructure facilities (Figure 7).

To overcome the limitations of hydrogen storage, the use of ammonia as the primary fuel was proposed with subsequent conversion to hydrogen. A modular design of local power sources was proposed, where each module is supposed to be built around a fuel cell. The capacity of fuel cells of different modules may vary.

The electrical energy output parameters of the modules are consistent with the parameters of the AC customer. In the absence of power from an external grid, one of the modules operates as the lead by voltage.

A power storage system on the basis of flow batteries was proposed. Research on the effective use of flow batteries for several modules of the same source will be carried out in the following works.

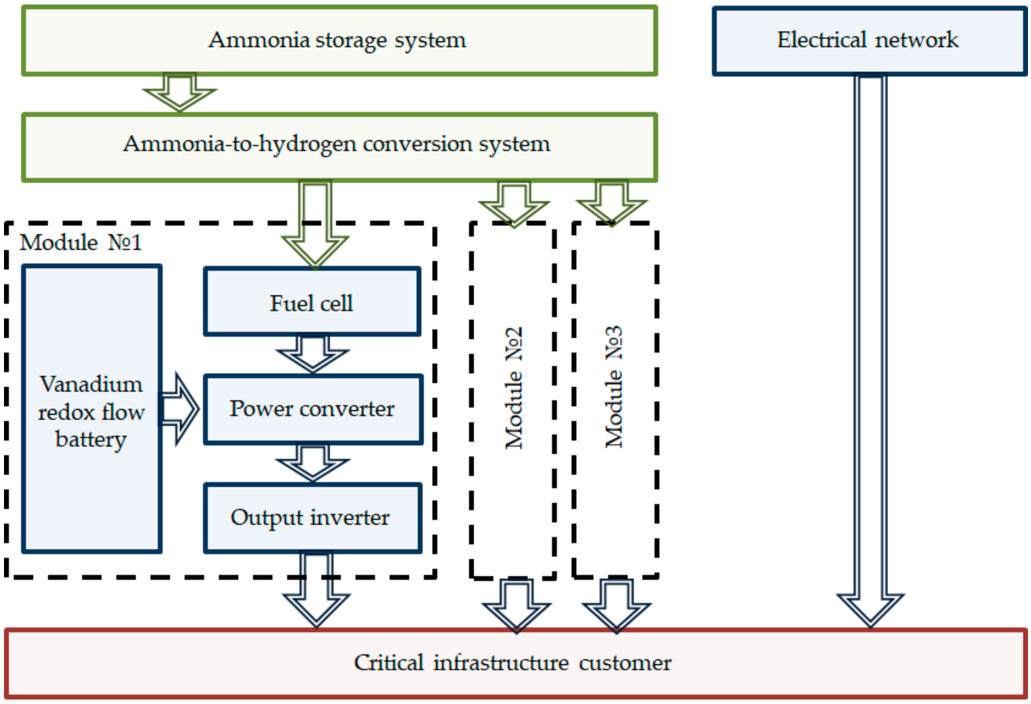

Figure 7. Prospective Fuel Cell-Based Local Power Source Structure for Critical Infrastructure Customers.

Each module should be fitted with its own control system (tier one) to control battery charge and the fuel cell operation mode. The customer, local power source modules, and external electrical network should be connected by a single control system (tier two). The purpose of the tier two control system will be to determine and set optimal operating modes and individual module loads (in particular, taking into account the increased life of fuel cells).

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