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The Concept of Autonomous Power Supply System Fed with Renewable Energy Sources

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ABSTRACT

Sustainable economic development requires the use of renewable energy sources in a rational and thoughtful way. In Polish conditions the use of several types of renewable energy sources on a single setup is a new issue. In particular, hybrid devices in conjunction with intelligent energy systems, such as lighting systems are generally not used. Therefore, the Polish energy production still relies on the burning of coal. Despite their advantages, renewable energy sources are characterized by seasonality and considerable instability. Access to renewable energy varies daily and seasonally, hence activities promoting the use of autonomous, hybrid power systems must be intensified. The presented research aims at the development of the Autonomous Power Supply (APS) system based on the so-called energy mix. Such a system works in an isolated arrangement and serves to reliably supply electricity from renewable sources for small residential or public utility devices in an urban area. Systems with up to 3 kW power consist of modules, whose modular design allows the combination of various power configurations and types of renewable energy used. The basic system consists of a primary power source, additional power source, emergency power source, energy storage device, weather station and controller. The energy mix depends on the geographical location of the system. The emergency source can be implemented as an on-grid connector or fuel power generator with the participation of 100% until the primary or accessory power source failure is removed. The energy storage system consists of batteries or supercapacitors. The proposed system can be combined to create a local network that automatically responds to energy shortages in various network nodes by adjusting the supply of electricity within the network depending on its needs. For Poland realistic solutions in this article are the new and modern answer to these requirements.

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KEYWORDS

Renewable energy sources, Photovoltaics, Wind energy, Smart grids, Micro grids, Autonomous power supply.

INTRODUCTION

In the not too distant past, there was a clear world-wide trend for scaling-up the industrial processes and devices. Now it seems that humanity, in the pursuit of increased production and consumption, has chosen the wrong path. That "scale-up" trend is now in reverse mode. Recent progress in micromachining technology brings benefits to carry out studies on microscale. Scaling-down the systems provides most of all the decentralization [1], but also higher effectiveness, lower costs, safe operation, easier control, less vulnerability to disorder and many more useful features. To obtain and test these results, it is basic to consider the size of the studied systems [2].

The prevalent theories in the debate on sustainability transitions have been criticised for not sufficiently addressing energy change processes at the local level [3]. Numerous contributions have dealt with decarbonisation, decentralization and the resulting shifts in politics and society as central elements in energy transition processes [4]. Globally, the power generation sector faces two major challenges based on the use of fossil fuels: high emissions of Greenhouse Gases (GHG) and the finite nature of fossil fuels leading to price increases in the long-term perspective. With renewable energy technologies both challenges could be addressed. They currently offer a cost-effective and sustainable way of electricity supply for large scale systems as well as for small island energy supply systems. Despite the obvious advantages of renewable energy systems on small islands their implementation is happening rather slowly. One major barrier is the missing knowledge about the existing techno-economic potential of renewable energy hybrid systems on these islands [5].

Large power plants are cost-intensive. Setting them up requires a lot of time on formalities, and during its operation, a lot of attention and care to maintain. An alternative to the large installations and energy networks, for powering facilities or equipment with low energy requirements and away from other networks, is the use of small or local networks in distributed systems [6]. Interest in this type of systems is growing rapidly as manifested in a multitude of different approaches to the problem. One of them is energy demand modelling of small objects. There are researches on automatic lighting systems [7], control system and technical management of the building on the example of a model apartment with assessment of the efficiency of lighting systems including luminescent and Light Emitting Diode (LED) lamps with a power from 276 to 576 W total [8]. For a complex of residential buildings modelling of micro-networks for heating, cooling and electrical energy management are compared with an analysis of the possible economic gains from the share of Renewable Energy Systems (RES), Combined Heat and Power (CHP) and energy storage [9]. Optimisation of such systems is performed via modelling of power demand variation for large residential areas including energy storage. The study lasting for the whole year included measurements every 5 minutes, averaged hourly is conducted for electricity and heat cogeneration system with fuel cells and energy storage [10]. For even more complex systems of residential buildings and industrial facilities research was made on monitoring and management of micro-networks with the participation of renewable energy sources in rural areas residential building and agro-industrial sites. Electric current comes from various sources like: public network, Photovoltaic (PV), synthesis gas and the engine, a wind power plant, heat comes from: the public network (gas), synthesis gas in a CHP, electric current from the public network. The object was monitored throughout the year [11]. Another approach is assessment of consumption patterns for large areas, consisting of residential buildings and industry, models and verification for the university campus, and the analysis of electricity consumption divided into lighting, heating and cooling [12].

Design systems for automatic control of the technical building management, consist of energy demand analysis [13] of independent, Autonomous Power Supply (APS) systems for electricity production [14, 15]. Such systems are usually designed based on renewable energy sources in hybrid arrangements [16, 17]. Proposed microgrid includes various energy sources such as photovoltaic array and wind turbine with energy storage devices such as battery bank. Micro grids are considered as Independent Power Producer (IPP) company in power systems and are subject of Particle Swarm Optimization (PSO) [18].

Such objects are usually based on a system size of the safe voltage levels, and may be 12 V or 24 V. This makes it possible to use low-voltage lighting LED bulbs. Further, as used in these systems the energy generating elements are mounted directly on the civil engineering work and will not exceed 15 m. Therefore, wind turbines do not require additional construction permits. For APS there are no energy losses occurring during transmission. Integration of the wind turbine and photovoltaic panels (binary system) is a desirable solution because photovoltaic provides the energy only during the day, while the wind turbines are able to produce energy both day and night. However, the use of a binary system does not guarantee uninterrupted supply of electricity. Therefore, APS should be expanded with the elements of improving its reliability such as an emergency power source. Or simply connected to the grid where applicable. The APS interest is rapidly increasing, because the devices powered by electricity are the foundation of the economy and the use of renewable energy sources is a necessity [19]. Renewable energy, particularly solar and wind power integrated with micro grid technology, offers important opportunities for remote communities to provide power supply, and improve local energy security and living conditions. The combination of solar, wind power and energy storage make possible the sustainable generation of energy for remote communities and keep energy costs lower than diesel generation as well [20].

THE AUTONOMOUS POWER SUPPLY CONCEPT

A typical APS system consists of several basic elements conceptually shown in Figure 1. They are divided into basic modules, i.e. the primary source of power, backup power supply, uninterruptible power supply, control system and energy storage. The circuit also includes a power system protection and receivers.

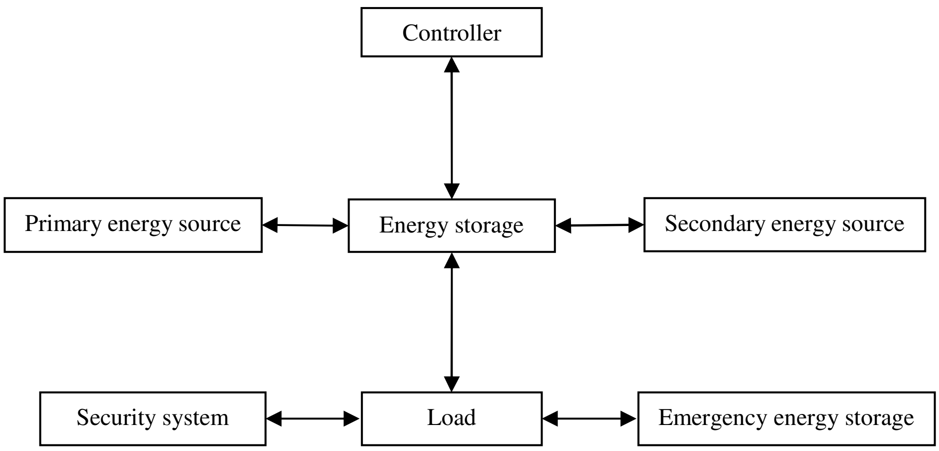

Figure 1. Block diagram of the Autonomous Power System (APS)

Expenditure on APS systems are very small, compared to the cost of large installations, the formalities related to the installation are kept to a minimum, and with so little expenditure, apart from profit, energy independence is gained, also reliability of modern solutions and additionally the pro-ecological feeling. The purpose of autonomous power systems, is electricity supply of houses, staircases, warehouses and lighting installations of small estates. APS are divided into 2 types, depending on the needs, placement and possibilities of their use.

The first is Island Autonomous Power System (IAPS) (sometimes called Rural APS – RAPS). It is used where there is no possibility of connecting to the grid, mainly away from built-up areas, but with the possibility of Horizontal Axis Wind Turbine (HAWT) turbine application. HAWT can be of larger size due to availability of more space. Island systems are more difficult to link to networks due to the considerable distance between them. The second type of APS is Urban Autonomous Power System (UAPS) (sometimes called Municipal APS – MAPS). This type of system should be adapted to the use of Vertical Axis Wind Turbine (VAWT) and should have the possibility of networking with other autonomous systems. VAWT is used due to less space and unsteady wind conditions.

The primary source of power should supply the system with the energy range from 60% to 80% of the demand. In most cases they will be using photovoltaic panels for direct energy production. Reserve energy feed system in the range of 20% to 40% of the load. It must use a different kind of energy than the primary source. Emergency source of electrical power to the system works at the time of failure or shortage of primary/secondary energy until the restoration of power from renewable sources. Energy storage may be, depending on one's needs and technical conditions, of storage battery or capacitor. Energy sources and energy storage connected to a common line in a buffer system enable bidirectional power transfer. At a time when the energy produced in the source is not used to feed the receivers, it is stored in the battery. In the event of shortages of energy from the primary source or a backup source to power the load, it is taken from the power bank.

Diversification of sources of supply is a basic issue and is dictated by the need to produce energy providing a continuous supply of energy to consumers. If the primary source of power is the photovoltaic cell that runs during the day, the backup source in the form of a wind turbine can successfully replace the primary source if needed.

RESULTS

As a result of the approach described in the above proposals, four different APS systems have been developed and tested: one for the laboratory performance tests, the second for lighting the residential building, third for workshop lighting, fourth for bus stop lighting. The proposed systems consist of the components shown in Table 1.

One way to use the APS unit is an intelligent lighting system of a bus stop, which uses APS described in Table 1. It uses simple drivers for switching the lighting information board through a proximity sensor. The load of LED lighting is 2 W. This APS system is proven to operate flawlessly and without interruption in the supply of energy for a year. Another way to use APS system is lighting of small workshop and garages. Location is very disadvantageous because it is situated in the city center and surrounded by higher buildings and trees. Along with the movement of the sun, moving shadows obscure the photovoltaic panels; hence the use of polycrystalline panels connected in parallel and partial shading does not interrupt the operation of the entire system. This APS uses a specially designed Carousel Vertical Axis Wind Turbine (C-VAWT), because in the center of urban development, there is no wind at a constant speed and C-VAWT turbine makes good use of wind gusts occurring between the buildings. For testing and laboratory purposes, a fourth APS was designed and built on the roof of our University and is shown in Figure 2.

Table 1. Components of the developed APS systems

		APS type			
		Laboratory	Bus stop	Staircase	Workshop
APS Components	Primary power system	6 × PV modules type: ET Solar ETP660240Wp	1 × PV modules type: 20 W 12 V Celline CL020-12P	2 × TSM-240PC05	4 × TSM-240PC05
	Primary total [kW]	1.44	0.02	0.48	0.96
	Secondary power	1 × HAWT type: Ista Breeze 500 W 24 V AC	none	1 × C-VAWT prototype	1 × C-VAWT prototype
	Secondary total [kW]	0.5	-	0.5	0.5
	Primary + Secondary total [kW]	1.94	0.02	0.98	1.46
	Emergency power	Grid connection	none	Grid connection	Grid connection
	Controllers	SMA Remote Control SI2024	TOS 10/24	TOS 30/24 ESOI v.15	TOS 50/24 ESOI v.17
	Inverters	SMA Sunny Island 2024 SMA Sunny Boy 1300TL	-	DC/AC	-
	Energy bank	4 × Victron Gel AGM 6 V/250 Ah	1 × MW 7.2-12L	4 × MW 14-12L	18 × MW 40-12
	Total storage	24 V 1,000 Ah	12 V 7 Ah	24 V 28 Ah	24 V 360 Ah
	Security	SMA Sunny Webbox	Power fuse	Power fuse	Power fuse
	Loads	Water pumping, site lighting, air conditioning	Showcases lighting	Staircase lighting	Lighting
	Total load	0.1-1.0 kW	1-3 W	5-30 W	0.8 kW

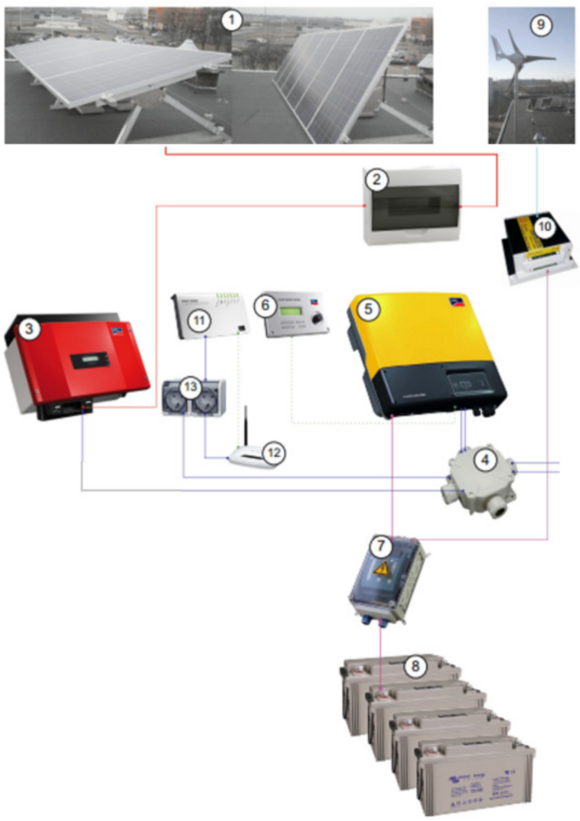

Figure 2. Diagram of the test APS built on the roof of Opole University of Technology building

For the needs of this project the Intelligent Lighting System (ILS) lighting system for 6-floor residential building was designed. Appropriate APS is described in Table 1 and schematic is shown in Figure 3. The components are further described in the sections below. Designed APS provides cover electricity consumption of 3 kWh per day in the period from March to October. In the remaining period of the year – 1 kWh per day.

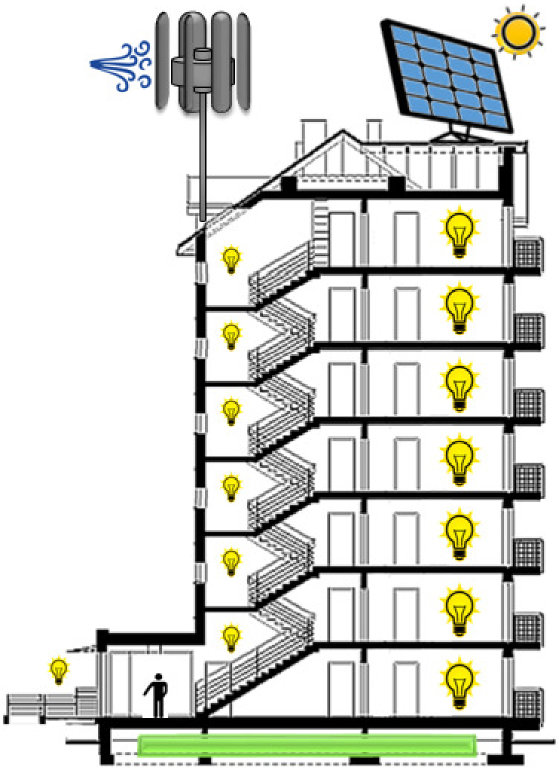

Figure 3. Schematics of the APS integration with the building, energy is harvested with C-VAWT and PV and stored is in the basement power bank

Primary power source

The basic power supply system should be designed to supply energy up to 80% of the total load. This should be a source of high reliability and efficiency. Ideally this is the role of photovoltaic cells. The primary power source of this APS consists of 4-6 polycrystalline photovoltaic panels connected parallel. The total peak power is 1,000 $W_{(peak)}$.

Secondary power source

The backup power source should use a different kind of energy than the primary source. If the primary source uses direct solar energy it is advisable to use wind energy (or, where possible, water energy). To do this, one can use VAWT wind turbines or HAWT. VAWT can be mounted almost anywhere, regardless of environmental conditions. They do not require the use of high masts and can even be mounted directly on buildings. Small wind power network (up to 10 kW) can be located directly at consumers of electricity and connected to the electrical system. This eliminates almost completely the energy losses in the electrical system and improves working voltage conditions of electrical appliances included in this installation.

Additional studies were carried out regarding the possibility of using certain wind turbine type. It has been found that it is highly dependent on the wind conditions prevailing in a given area, that is, the height of the turbine and in highly urbanized areas, additionally the specific local conditions.

Small-scale wind turbine operation within the urban environment exposed to high levels of gusts and turbulence compared to flows over less rough surfaces [21]. The area of air masses movement can be divided regarding the altitude into three zones:

Ground level zone. This zone is located up to a few meters above the ground where the air flow brings low amount of power. Installation of wind turbines in this area is uneconomical.

Architectural zone. This zone is located up to several meters above the tallest buildings or objects in the considered area. The winds that blow in it have significant energy resources, but their nature prevents the use of turbines HAWT due to gusts and frequent change of wind direction.

Energy zone. This zone is located above the architectural zone and is characterized as a stable direction and speed of air mass movement [22].

An interesting area for us is the architectural zone, where there are objects subject to energy supply. In the architectural zone wind has high direction volatility, rarely occurs in a plane parallel to the ground and is often in the form of gusts. In these areas the use of Urban Autonomous Power Systems (UAPS) becomes relevant, because the C-VAWT carousel turbine is designed for the most of such conditions. They do not require guidance systems for wind, have low inertia, which allows them to take advantage of wind occurring in strong gusts and are very good in using the wind blowing in different planes. They do not also have the need of special bearings or gears, which are prone to failure in larger scale [23]. Therefore, the set up APS will consist of prototype carousel wind turbine with a 5-bladed rotor with active surface of 1.2 m^2 and a power of 500 W. The wind turbine has a structure consisting of the 5 blades of a characteristic shape attached to the axis of the turbine. The power generator is in the housing (Figure 4).

Figure 4. The prototype carousel-type vertical axis wind turbine C-VAWT designed for the powering of the developed APS system

Energy storage

The most common energy storage system consists of electric accumulators gathered in batteries. Acid batteries with gel electrolyte are cost-effective and most commonly used. Technical parameters of the gel batteries are the voltage and capacitance. Battery voltage is mostly 12 V. Less frequently 6 V or 24 V are used. Batteries connected in groups are called storage banks and its connection obtain various options for voltage, current or capacitance. Energy storage should be selected in such a way that its electrical capacity is sufficient to meet the needs of power for a period of 3 to 6 days. Energy storage for the planned APS is a battery of gel accumulators connected in series-parallel with a voltage of 24 V and a capacity of 360 Ah. The move toward mobile power sources has placed ever more severe requirements on batteries, and necessitates every possible performance improvement that can be made. One strategy that is taken as axiomatic is placing a super capacitor (or bank of super capacitors) in parallel with the battery [24]. Despite yet fairly high price, they have many advantages such as very high rate of charge/discharge [25, 26].

Controller

The controller used in the proposed APS is an integrated system controlling the photovoltaic and wind turbine. It is equipped with Maximum Power Point Tracking (MPPT), and an DC/AC inverter. Systems of this type help to save energy, control the operating parameters of devices within the system and to increase the comfort. It is important to devote them a lot of attention. One such device is energy-saving ILS, built on the microcontroller ATMEGA (Figure 5). Microcontroller connects sensors, lamps and administration panel that communicates via the Ethernet/GSM/GPRS, which enables centralized management and optimization. It also allows for the development of the project, transforming the place of installation of the smart area of taking care of our comfort and safety. Construction of the controller is modular and can be extended and equipped with other modules such as data recorder, electricity consumption meter and other software. Use of proven components for a new generation of electronic assembly technology (SMD, MOS-FET) allow to simplify design, extend its life and reliability as well as lower the cost, extends trouble-free operation of the system, while limiting the energy consumption and maintenance costs to a minimum. Similar controllers are now the subject of rapid development and one of the most interesting examples is Lightwatcher system, a system that allows creative lighting mode [27]. Energy-saving controller that is capable of shaping the light output of an LED lighting system autonomously based on data received from sensors is good enhancement of standard lighting systems. Intelligent lighting systems seek to achieve this by utilizing integrated sensors to provide feedback in a closed-loop control system. A common energy-saving technique is occupancy sensing, which obtains feedback from integrated occupancy sensors [28].

Figure 5. Intelligent Lighting System (ILS) controller interface

Emergency power source

It is needed for the objects to have ensured continuity of energy supply. This may be an internal combustion generator or switch on-grid, connecting the system to the power grid. In this case, if the link on-grid is applied, the network can provide energy storage.

DISCUSSION

Rising carbon emission or carbon footprint imposes grave concern over the earth's climatic condition, as it results in increasing average global temperature. Renewable energy sources seem to be the favorable solution in this regard. It can reduce the overall energy consumption rate globally. However, the renewable sources are intermittent in nature with very high initial installation price. Off-grid Small Autonomous Hybrid Power Systems (SAHPS) are a good alternative for generating electricity locally in remote areas where the transmission and distribution of electrical energy generated from conventional sources are otherwise complex, difficult and costly [29].

In Polish conditions the use of several types of renewable energy sources on a single setup is a new issue. In particular, hybrid devices in conjunction with intelligent energy systems, such as lighting systems are generally not used. Therefore, Polish energy production still relies on the burning of coal. In addition, because the access to renewable energy is varied daily and seasonally, activities promoting the use of autonomous, hybrid power systems must be intensified. Proposed solutions in this article are the new and modern answer to these requirements.

CONCLUSION

The advantages of developed APS and ILS are as follows:

- Hybrid technology, which allows energy source diversification and independent operation;
- The buildings that have a unique APS are transformed into an independent energy system;
- The user in the building is accompanied by lighting – light moves with the user. Switching the lights is performed in the delta mode, i.e. on the current floor, lower floor and upper floor in the stairwell. Linked three floors are triggered by a sensor. Systems runs smoothly when there are two or more users in different floors;
- When a building enters in EMERGENCY state (in case of fire, etc.), system cuts off grid power to the building. Despite that the staircase is illuminated, which enables effective evacuation, and the energy stored in batteries to provide power for the duration of rescue operations, even after a power cut in the building;
- APS and ILS allow remote management of lighting through the internet according to user preferences, for example: in order to perform a diagnostic test, turn off the desired part of the building lighting, illuminate special, custom pattern etc. The number of applications is limited only by user imagination;
- APS and ILS allow equipping the controller with various sensors such as smoke detector, carbon monoxide, dangerous gases, extreme temperatures, protecting users against the dangers;
- The future lies in optimizing APS according various weather data over past several years, which include wind speed and solar radiation.

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