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Preface

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Roadside infrastructure unit as an autonomous small-sized smart grid. “Holonic” approach

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Abstract. Along now being constructed Western Europe to Western China (WEWC) Corridor big territories are totally uninhabited. It leads to absents of any central power supply. While transport infrastructure and control on the highways should be provided. The article is devoted to autonomous power grid of such road unit as a transport control post “Rubej”. Firstly, the scientific analysis of renewable energy sources of the republic of Kazakhstan and justification of exact power plants for the post is provided. After that the research is focused on a principle of power grid control. The “Multi-agent system” (MAS) technique was proven to be promising approach to the smart grid’s design. The one of the recently offered MAS techniques is the Holonic architecture. While it was adjusted only for power grids with central grid connection. In the article autonomous smart grid based on Holonic approach is offered and described. The optimization problem for the control of autonomous small-sized smart grid is reckoned. The achieved results can ease the control system’s design and scaling process, as it should be provided even for small-sized grids. In the end financial actuality is proved.

1. Introduction

Planned length of WEWC Corridor is 8 445 km. While 2 787 km are passing through Kazakhstan territories with very rarefied population: 17 476 141 people at 2 724 000 km2 (the ninth place worldwide for territory) [1]. Consequently, most of the highway will go through areas without any central power supply. It leads to entanglements in power supply for any remote element of road infrastructure. In particular, modern supporting equipment for transport control post “Rubej” became more intellectual and demand stable electric power supply.

According to Igor Lepeha – chairman of Committee of Administrative Police of Ministry of Internal Affairs of the Republic Kazakhstan – there are still no enough “Rubej” control posts on the territory of republic. For existing roads 44 posts are necessary, while only 35 is active. And even them not always have proper living conditions. Whereas more traffic routes are constructed for WEWC Corridor, and most of them bypassing functioning posts. [2]

Plants based on renewable energy sources (RES) can provide enough amount of power. It includes combination of wind turbines and solar plants depending on geographical location of an exact post. According to the researches at a southern areas of Kazakhstan there are up to 3000 hours effective for solar plants, which leads to nearly 1 500 kW/m2 annually. At the same time half of the territory is suitable for wind resources’ utilization as average wind speed is more than 4 m/s. [3]

With RES implementation uncertainty of power grid parameters arises. Power storage by electric accumulators and convenient reserve fuel generator can partly solve the instability of the power sources [4]. With such a complexity of equipment manual control can provide some inappropriate dispatching of the grid elements. While control system design for every exact autonomous power grid's set claims too much human resources. A universal optimization technique for a grid can become a proper solution for the problem.

The second part of the article is devoted to description of such roadside infrastructure unit as a transport control post. On that basis its power consumption is calculated. In the third part information about power supply elements is provided, their choice and technical characteristics are justified. Afterwards the control approach for the autonomous power grid on renewable energy sources and the optimization problem as an implementation on the control post are offered. In following part reckoned power grid structure and elements' interaction is discussed. Next part is devoted to compare possible investments with other solutions. Finally, implementation possibilities and future improvement of the power grid is considered.

2. Power needs of a transport control post

Stationary transport control post "Rubej" is specially designed building with all necessary operational and technical equipment to accomplish functions of: Traffic control, ensuring road security, an offence registration, ensuring officers' welfare.

Traffic control function is provided by automated system "Post-Rubej". It fully automatizes registration and search of passing traffic in data bases about stolen vehicles, tax dodgers. Above that, stopping technique is automatized too.

Main functionality of the system is:

- Fixation and recognition of a state number;
- Record of traffic data into local data base (DB);
- Simple but secure access to the DB;
- Search of recognized numbers in DB about tax dodgers;
- Search of recognized numbers in any other local DBs;
- Automated control system for traffic regulating equipment;
- Integration to existing information systems of the Ministry of Internal Affairs. [5]

Hardware of the system consists of digital camera with high sensibility in infrared diapason, speed radars, infrared lighting, computation modules. [6]

Road security is ensured partly by the "Post-Rubej" system, partly by officers' work. Consequently, no additional hardware is needed. An offence registration requires a computer, a printer and a connection to the Internet. For a light system power saving LED lightings and movement indicators are expected. While to ensure officers' welfare the post can be equipped with refrigerator and microwave cooker.

2.1. Power calculation

The power consumption of previously mentioned equipment can be divided into two main groups as was offered for an autonomous power supply at Tunisian petroleum platform [7]: mandatory and welfare. Mandatory consumption is a sum of demands from exact operating hardware. For the transport control post they are automated system "Post-Rubej" and an offence registration's hardware. While welfare consumption consists of lighting and welfare equipment. Such division generates one more possibility for control in an autonomous power grid. The possibility is to make recommendation on or even switch off the welfare demand. Difference between the platform's and the post's supplies are in the level of demanded power, in availability of fuel and in possibilities to connect with other grids – central as a consumer or neighboring micro-grid as a supplier. For the post level of power supply is lower, but the electricity's quality should be much better. The fuel is available on demand, while for the platform it is limited. The future possibility to become a part of bigger grid for the post's power grid is much higher, as the road infrastructure usually is growing.

The exact electric power demands for both parts are shown in table 1.

Table 1. Daily electric power needs of stationary transport control post "Rubej"

Equipment	Amount	Required power, W	Working hours	Watts per hour
		Mandatory part		
Digital camera	2	27.0	24	1 296.0
Speed radar	2	3.8	24	182.4
Infrared lighting	2	1.2	12	28.8
Computation module	2	30.0	24	1 440.0
Traffic light	2	20.0	24	960.0
Boom gate	2	150.0	4	1 200.0
Officer's computer	1	120.0	24	2 880.0
Printer	1	100.0	1	100.0
Wireless connection module	1	30.0	24	720.0
Total for mandatory part	-	482.0	-	8 807.2
		Welfare part		
LED lighting	4	20.0	10	800.0
Refrigerator	1	150.0	4	600.0
Microwave cooker	1	700.0	4	2 800.0
Total for supplying part	-	870.0	-	4 200.0
Total	-	1 352.0	-	13 007.2

While the calculation of power peak level is done with:

$$P_{peak} = \sum_{i=1}^{n} P_i \quad (1)$$

where P_{peak} is a peak power, W; P_i is a required power for i^{th} equipment unit, W; n is a number of equipment units.

Also for supplying plant's choice daily required electric energy is necessary:

$$E_{total} = \sum_{i=1}^{n} E_i = \sum_{i=1}^{n} P_i \cdot h_i \quad (2)$$

where E_{total} is a total electric energy needed, W·h; E_i, P_i and h_i are an electric energy needed, a required power and working hours of i^{th} equipment unit, W·h, W and h respectively; n is a number of equipment units.

Total peak power demand is up to 1.4 kW and daily power consumption is calculated just higher than 13 kW·h. Mandatory consumption, that is less than 0.5 kW – peak demand and less than 9 kW·h – daily, cannot be ignored. As for welfare needs, that are less than 1 kW in peak and less than 4/5 kW·h – daily, it's supplement can be controlled or even switched off, if both main generation is absent and accumulators' charge is not enough. A user can be consulted by a smart grid when and on which level the power grid can assure welfare power consumption for him to choose which welfare needs can be ignored.

3. Power needs of a transport control post

Research of the RES potential in Republic of Kazakhstan shows that mainly territories have average wind speed above 4 m/s [3]. So, use of small power wind plants is appropriate there as have been justified by previous research [8]. At the same time, on most geographical areas daily solar radiation is in average 0,3 kW·h for m2 [3]. That proves the possibility to utilize solar plants.

Whereas power demand is less than 1.5 kW in peak, power supply system as a complex of three parts is offered:

- Main supplying plants – wind turbine and several solar plants;
- Buffering equipment – electric accumulator;
- Reserve supplier – fuel generator.

The main criteria of choosing power plants are matching RES potential at exact geographical position and providing all the peak power demand at the nominal operating time. The potential should be calculated by a real data or by RES maps [3]. But, preliminarily, more solar plants and smaller wind plant is recommended in southern parts, while vice versa – in northern and western regions.

Consequently, both wind turbine and solar plants' complex should match minimum nominal power level of 2 kW. While average wind speed is nearly 4 m/s, which limits our wind turbine's choice only for low-powered generators.

For a wind utilization autonomous wind power plant (WPP) "LOW WIND 2.5/3.5 kW" was chosen. Wind speed limits for nominal work is between 2.5 and 25 m/s. It's nominal and maximum power is 2.5 and 3.5 consequently and output is 24 V of DC [9]. The plant can provide more stable work by the small winds and cover the power demand from both the post and the accumulators at nominal speed. Although at average wind speed of 4 m/s its output will be just higher than 0.5 kW [9].

According to the mandatory consumption that is equal to almost 9 kW·h daily 8 solar panels with 260 W power are chosen [10]. It leads to total coverage over the control post's electric power demand in sunny hours, while charging accumulators, if consumption is not in peak.

RES plants are supplying the system with electric power of such properties it should be processed by an inverter. The inverter changing unstandardized currency into proper AC or DC. For the plants' implementation the Tripp Lite APSX3024SW inverter is found. It's nominal and peak input power is 3 and 4.5 kW respectively as the plants' maximum output is just bigger than 3 kW. The inverter provides pure sinusoid with 230 V [11].

At the time when neither sun nor wind is not in charge electric accumulators should be used. 8 pieces of „CHALLENGER A12-200" accumulator are chosen. By 12 V and 200A·h they are providing 19.2 kW·h [12]. Consequently, the accumulators can fully supply the control post for 35 hours without RES plants' input.

The last part of supplying system is a fuel generator. The main criterion is to fully supply the control post, if neither RES plants nor accumulator can provide electricity. As the control post consumption is less than 1.4 W at a peak time the diesel generators are unsuitable. Also the electronic devices demand electric power of a good quality. Within this context SAP·35 inverting petrol generator was chosen. It's nominal power in 3.5 kW with ideal 220 V and 50 Hz of AC. In addition to that, in a condition of small loads the generator reduces fuel consumption up to 40 % [13]. Other advantages of the petrol generator are the wider temperature limits and higher popularity of petrol in automobile sector of Kazakhstan.

All chosen for the supplying system devices can provide energy enough for the control system demand as can be seen in table 2.

The peak supply of WPP covers all consumption and accumulators charge, while solar plants can provide energy just for peak consumptions. If neither of the sources will be unavailable, accumulators can supply full system's demand for 1,4 days and mandatory demand for more than 2 days. If in two days the RES will be still unavailable, the reserve generator can be used. And, while the reserve generator works on petrol, the availability of the resource is high enough.

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Table 2. Electric power supplying plants

Equipment	Amount	Nominal power, W	Peak power supply, W	Other parameters
Wind plant “LOW WIND 2,5/3,5 kW”	1	2500.0	3500.0	Wind speed: 2.5-25 m/s
Solar cell array “LDK-260PA”	8	260.0	2080.0	Nominal voltage: 24 V; Size: 1636×986×35 mm
Inverter “TRIP LITE APSX3024SW”	1	-	-	Nominal input power: 3 kW; Peak input power: 4.5 kW
Accumulator „CHALLENGER A12-200”	8	-	-	Nominal voltage: 12 V; Nominal capacity: 200 Ah
Reserve inverting petrol generator “SAP·35”	1	3500.0	3500.0	Nominal output: 220 V, 50 Hz of AC

4. Smart grid based on “Holonic” approach

First step to design a control system is to choose an approach of elements’ interaction within a controlled object. In power systems the “Multi-Agent System” or MAS technique is offered as the advanced power grid’s structure [14, 15]. It gives possibility of control and adjusting to lower level of the grid (even till a client or a house) and decreases the data processing loads on the central grid’s controlling system. The disadvantage of classical MAS is in necessity of different mathematical description for the grids’ elements at every level.

The offered in the article MAS approach is based on “Holarchy” theory. It is similar to “system-subsystem” structure from classic MAS in dividing a whole object into smaller parts. The difference is that smaller parts – Holons – in the Holonic architecture have the same mathematical description as the object itself. It leads to easier scalability of the designed control system. Recently the Holonic architecture was adjusted for optimization of materials’ flows in manufacturing systems and their control [16]. The architecture was offered for thermal power systems as the thermal power grids have similarity with manufacturing in materials’ flows [17]. As there is straight connection between materials’ and energy flows the next step was to research the possibilities of Holonic architecture’s implementation in electric power grids. Consequently, the perspectives of such approach for electric power was justified [18]. The concept of smart grid’s optimization in multi-agent power grid by Holonic architecture was researched [19, 20]. But neither of them discussed the autonomous power grid optimization and control, while the transport control post requires autonomous electric power supply.

For Holonic architecture the elements of power grid should be categorized into consumers, suppliers and elements with mixed characteristics. The main example of mixed element is accumulator as at some point of time it can be a supplier or a consumer. Holons of the higher level can be a combination of lower level Holons based on Holons’ type or their physical connection within a power grid.

For the control post’s power grid as a Holarchy 5 lower level Holons, as can be seen from figure 1, are offered.

Lower level’s Holons are:

- 3 supplying Holons: WPP, Solar plans and reserve generator;
- 1 consuming Holon: all power consuming equipment;
- 1 mixed Holon: combination of all accumulators.

While solar plans’, consuming and mixed Holons have even lower Holons. For solar plants’ Holon they are every exact solar cell arrays, for consuming Holon – mandatory and welfare consumptions, for mixed Holon – all 8 accumulators.

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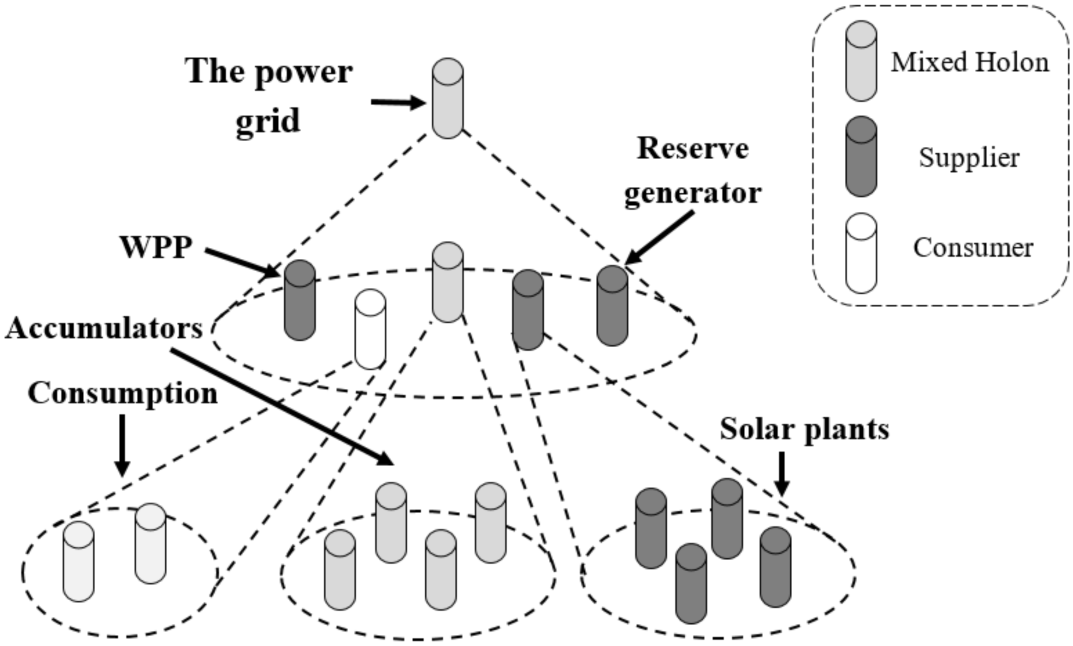

Figure 1. The control post's power grid as a Holarchy.

4.1. Mathematical description of the power grid as a Holon

The real power consumption of the power grid is uncertain value, but with known peak value and total daily amount. In such small power system recommendations about welfare consumption's value in exact time period for person as a consumer can be given. While, with possible future redesign for supplying neighboring entities, the consumption forecasting as uncertain value will be necessary [15].

The supplying plants on RES have uncertain output values too as they depend on weather conditions.

For solar panels' output such dependency will be:

$$P_{ss} = f[G(\beta,\alpha), T_C] \tag{3}$$

where P_{ss} is an output power of a solar array, W; $G(\beta,\alpha)$ is an incident irradiance on the plane of the array, W/m^2; T_C is a cell temperature, °C. [20]

The WPP's output is also a function from weather conditions:

$$P_{sw} = f[\rho, v_w] \tag{4}$$

where P_{sw} is an output power of a plant, W; ρ is an air density, kg/m^3; v_w is a wind speed, m/s. [21]

As can be seen from equations (3) and (4) both power supplies have straight connections with weather conditions and are calculated for next hours with use of weather forecasting from Internet. That gives certain error to the calculation within the control system.

The uncertainty of the system is balanced by power accumulators, which are working as a buffer to collect and store power surplus and use it when power plants are off. Electric accumulators' charging limits have to be taken into consideration. As the capacity of them are decreasing while they are over- or undercharged.

4.2. Optimization problem for the Holon

There are two possible ways to balance the system at the power lack: to use power from batteries and to make recommendations on or even switch off the welfare power consumption. The choice of the system should be based on weather forecast and on accumulators' conditions.

The power supply and consumption in the power grid is considered negative and positive value respectively to calculate the resulting power balance. Then the total power at the exact time in the grid can be calculated as a sum:

$$Pt = \sum_{i=1}^{n} P_{si} \tag{5}$$

where P_t is a total power in the grid, W; P_{si} is a power of i^{th} Holon, W; n is a number of Holons in Holarchy.

Then the optimization problem of a Holarchy without any power storage is formulated as minimization of the sum (5) online:

$$Pt = \sum_{i=1}^{n} P_{si} \to \min \tag{6}$$

The control actions will be switching on/off or demanding exact power value from the Holons.

The optimization problem (6) is the mathematical description for Holons of middle level from figure 1: the solar plants, the consumption and the accumulators.

While for autonomous power grid there is no external output for the surplus. And the optimization problem (6) will be specified as:

$$Pt = \sum_{i=1}^{n} P_{si} \to 0 \tag{7}$$

With implementation of accumulators control action are extended by choosing a state of accumulators between supplying or consuming. That demands not an online but planned control. To calculate the exact period of planning the chosen accumulators' capacity have to be considered. Fully charged they can supply the grid for 28 hours and have enough energy to supply mandatory need for more 24 hours.

Consequently, the final optimization problem is formulated like:

$$\begin{gathered} \sum_{j=1}^{28} P_{tj} \to 0 \\ SoC_{\min} < SoC_j < SoC_{\max} \end{gathered} \tag{8}$$

where P_{tj} is a total power in the grid at j^{th} hour, W; SoC_j is an accumulator's state of charge at j^{th} hour, %.

Then the practical calculation of control system for the smart grid is to find optimal controlling values for next 28 hours on the basis of the formulated optimization problem. There are various techniques to calculate it: classical or advanced. Classical optimization techniques are fully automatized by special software and can be directly implemented to a controller. While advanced techniques are fully described by exact researches and can be implemented into controller's software too. For example, hyper-spherical search was proved to be the best for non-linear optimization [22].

5. Power grid control and interaction between elements

The control system consists of 9 elements as shown in figure 2: mandatory and welfare power consumption, WPP, solar plants, accumulators and fuel generator as power elements; dispatching block, controller and internet connection as controlling elements.

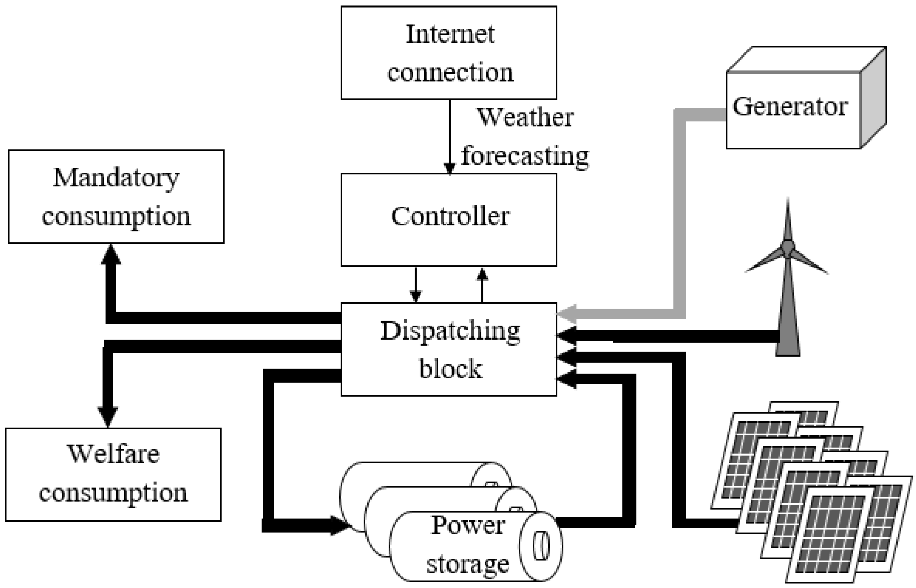

Figure 2. The smart grid structure and interactions between elements.

Within the power grid as a Holarchy there are three Holons on which system cannot affect: WPP, solar plants and mandatory consumption. Three other Holons – welfare consumption, set of accumulators and fuel generator – can be used as a controlling instruments. All of them are connected through dispatching block, where physical switching is happening. While the inverter is also a part of dispatching equipment. The decision for the dispatching block is provided by controller, where current and future states of the grid is processed and exact solution based on previously stated optimization problem is found. To calculate the future power supply of the grid weather forecast through internet connection is used. The connection of fuel generator differs from others as it operates manually, if plants on RES are not giving energy for more than 2 days.

There are more advanced and expensive smart grid structures with load forecasting and data analytics as in CompactRIO complex [23]. It's actual for a grid with several consuming entities or very unstable consumption. While at the control post power is demanded on a regular basis with almost exact amount. And the welfare part of consumption can be regulated by straight interaction with the officers.

6. Financial actuality

The alternative way to supply the control post with power is to provide connection to a central grid. The cost of 1 km of electric lines will be at least 7 921 € [24]. While the small-sized power grid cannot connect straight to the central power line. It leads to increase in the cost by more than 1 802 € for a power substation [25]. After that investment, also monthly payment for electricity should be done. The offered power grid cost is less than 12 500 €, as it needs 10 325 € for power equipment (4 485 € – for wind plant, 1 160 € – for solar complex, 1 340 € – for inverter, 3 163 € – for accumulators, 177 € – for fuel generator) [9-13] and less than 1 000 € – for controlling equipment [26]. While operating expenses will be only for service and petrol's cost in situation of total RES' absents for 2 days.

7. Conclusion

The number of roads in Republic of Kazakhstan is growing fast because of the WEWC Corridor. Most of the roads demand electric power supply to provide proper infrastructure. While with small population of the country road networks are wider presented than electric power networks. It leads to increasing investments of the government or limitations in posts positioning on a road.

On the republic's geographical territories RES, especially solar radiation in southern parts, are highly represented. RES' potential and calculation of power demand of the transport control post was compared. It was stated that the autonomous power supply on RES' plants can fully supply the post. As a result, the complex of power plants on wind and sun energy for the control post's supply is offered. The inverter to ensure proper quality of output electric power is chosen. For periods of time when there is no power production from RES the accumulators as a power buffer is stated. The chosen accumulators can provide full power supply for the system for 35 hours or full supply for 1,4 days with 2 days more for only mandatory supply.

Design of any exact control system is a complex engineering problem. While with proper mathematical description of an object and, if there are, an optimization problem the complexity of the task decreases. The MAS strategy is proved to be a promising designing instrument for power grids of any size. While Holonic architecture gives opportunity to divide system into parts and formulate same mathematic description for both system and its parts. The previous researches justified optimization techniques only for systems with connection to central grid. In the article, after applying this technique on the control post's power grid and receiving structure of the Holarchy, the optimization problem for autonomous power grid with power storage is deduced. While calculation of optimal controlling values can be provided online with special software within an implemented controller. The functional scheme of the smart power grid is reckoned. As a result, offered approach and formulated optimization problem gives the possibility to design control system ones and scale it to other power grids with less research. Also it provides possibility to optimally dispatch the power grid with minimum human participation.

The known alternative for the remote small-sized power grids is to provide electric over-head line from a nearest central grid's connection. Also some simplest transformer sub-station is needed. So, the possible cost of such connection is rising upper than 9 723 € for equipment for 1 km distance. While offered power supply on RES with all power and control equipment will cost nearly 12 500 €. And with almost no operating costs, beside service and some fuel, the autonomous power grid is beneficial in all expenses. In fact, such remote post can have some neighboring entities, that are distant from central grid too. That means that such power grid can provide energy to some neighbors as clients, which leads to additional financial and social effects. It demands only small redesign in power plants and control algorithm, which have been eased by the offered Holonic approach.

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