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COST-BENEFIT ESTIMATION OF THE SMART GRID DEVELOPMENT FOR THE RUSSIAN UNIFIED POWER SYSTEM

The paper is devoted to the issue of smart power system cost-benefit analysis. The innovative character of smart grids is defined and related obstacles for traditional cost-benefit assessment are revealed, primarily referred to external effects evaluation. Brief systematization of existing methods of smart grids assessment is provided and their weak points are defined. A new Smart Grid cost-benefit assessment approach is presented, basing on the elaborated comprehensive system of smart power system effects. The approach is tested for the system effects of smart power system implementation in the Russian Unified Energy System, quantitative results are presented.

Key words: smart grid, economic efficiency, cost-benefit analysis, prosumer

JEL classification codes: L94, O22, Q47

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1. Introduction and Theoretical Foundation

Smart Grid proves to be a holistic technical platform, which meets the energy needs of the innovative 21st century economy, post-industrial society requirements, sustainable development needs. Active Smart Grid strategic planning, constantly increasing scope and number of innovative projects (DOE, 2009; Mercom, 2010) in the area of transmission and distribution, active consumers and prosumers, distributed generation, are driven by system challenges of the 21st century economy, which modern electric power industry has encountered.

Smart grid is considered in Russia and in the world as a momentous area of scientific and technical progress in electric power industry; it is an object of Energy Institute of the Higher School of Economics' research, in particular, the institute focuses on system priorities of technological development in Russian energy system (Gohberg, Filippov, 2014). The researches are performed in a close interaction with Energy Research Institute of the Russian Academy of Sciences, being a center of scientific and technical projections in the field of energy efficiency.

The main drivers stimulating the shift to the new energy supply philosophy, technical means and control systems, vary from country to country[1]. We differentiate the following the most important drivers as a result of a conducted desk research:

1) decrease in economic losses of final consumers because of improvements in reliability and quality of their power supply, primarily taking place in "digital" economy sectors;

2) integration of renewables and electric vehicles in power system; it is vitally important for substantial advancements in greenhouse gases emission reduction;

3) enhancement of retail market competition through active consumer participation and distributed generation development, that will create new conditions for market pricing on the basis of local demand and supply equilibrium;

4) integration of power systems and markets, creating new opportunities for the wholesale competition and optimization of energy resources consumption on a national scale.

In long-term prospect the above listed drivers will partly influence the strategy of "smartening" the power sector in Russia, but it is already obvious that the design of Russian smart energy system will be different from European and the US samples. The problem to find a way to estimate costs and benefits from smart energy system introduction in the country already needs to be tackled, it is currently elaborated by Russian researchers (Kobets, Volkova, 2010; Volkova, Bushuev, Veselov, 2012) as well as foreign institutes (EPRI 2010, 2011; Giordano, 2012). Existing approaches proposed by leading international institutes cannot be directly applied for the smart energy system evaluation in Russia because of the specific features of national Unified Power System, including the highly centralized nature of its operation and

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[1] See for ex. (DOE, 2003; NEB, 2010; METI, 2010)

development and an important role of system-wide technical effects and economical consequences.

The approach presented in the current paper is aimed at inclusion of the systemic context in cost-benefit assessment of a smart power system and can be applied for system-wide evaluations of “smart reshaping” of power systems in other countries. The general methodological approach step-by-step description contains main principles which should be applied in smart power system feasibility study, and presented smart power system effects systematization helps to distinguish the levels and the sources of the effects. The part of the approach, namely, evaluation of system effects, was tested for the Russian Unified Energy System.

The first part of the work deals with the theoretical foundation behind Smart Grid projects economic evaluation, then Smart Power System (SPS) effects are discussed and classified, and the proposed approach to SPS system effects assessment is presented. Main system economic effects values for the Russian SPS are included in the final part of the work.

Theoretical foundation behind the Smart Grid development and implementation remains relatively incomplete (Massoud & Wollenberg, 2005).

Smart Grid relates to innovative projects by the range of features. Joseph Schumpeter defined economic development as a cyclical process driven by innovations (Schumpeter, 1961). Electric power industry is still based on 100-year old technologies, which do not perfectly meet the needs of the society and economics in the new century. Accumulated technological and IT innovations integrated by Smart Grid system enable the transition to a completely new level of electric power industry organization. Postindustrial economy widely employing information technologies, on the one hand, requires appropriate electric supply, and on the other hand, makes it possible to develop.

J. Schumpeter distinguished five different types of innovations: new products, new methods of production, new sources of supply, the exploitation of new markets and new ways to organize business (Schumpeter, 1961). Smart Grid integrates new methods of supplying electricity, enables new sources such as renewables and storages, opens new markets (retail electricity market and related services market) and changes the traditional business formats of electric power utilities.

Consequently, methods and principles for innovation projects assessment theoretically can be applied to Smart Power System development evaluation, in theory.

Cost-benefit analysis is a general approach to investment and innovative projects’ evaluation. It implies financial measurement of costs and benefits of the projects during its life cycle and their comparison using the set of indices (Greenberg et al., 2006). “Cost-benefit analysis is a practical way of assessing the desirability of projects, where it is important to take a long view (in the sense of looking at repercussions in the further, as well as the nearer, future) and a wide view (in the sense of allowing for side-effects of many kinds on many persons, industries, regions, etc.), i.e., it implies the enumeration and evaluation of all the relevant costs and benefits" (Prest, Turvey, 1965, p. 683).

Researchers admit significant obstacles for cost-benefit analysis application to wide-scale innovative projects (Prest, Turvey, 1965; Sager, 2003). Innovative projects are characterized by the high level of uncertainty, relating to externalities' volume and beneficiaries. That is why welfare economics theories should be employed for innovative projects analysis, in particular, externalities theory (Pigou, 1912).

We conducted an analysis of existing publications containing quantitative cost-benefit Smart Grid estimations. They all can be referred to a project-scale assessment and can be divided into two main approaches:

1) Standardization of the functionality options for Smart grid technologies. This approach implies algorithmic evaluation of costs and benefits of the selected technologies set and was offered by EPRI (EPRI 2010, 2011). European institute Joint Research Center adopted the approach and modified it to take into account existing European strategic documents. (Giordano, 2012)
2) Gap-analysis for extended costs assessment (including regulatory and technical policy, consumer systems) and expert estimate of benefits (WV SGIP, 2009).

The presented evaluation algorithms do not cover a set of Smart Power System features, such as complexity, interrelations between smart technologies and control methods and important synergy effects, with respect to the power system itself. In addition, each country case needs its own investigation, taking into account its power system characteristics and strategy. The flaws in the existing methodological background of smart power system cost-benefit evaluation defined further investigations of the Energy Research Institute of the Russian Academy of Sciences. In particular, existing smart grid effects classifications were reviewed and a new systematization was formed to define local and system-wide technical and economic effects from a smart power system implementation for their further quantitative evaluation.

Therefore, current paper has the following research question: what is the algorithm of smart power system cost-benefit analysis that avoids weaknesses of existing approaches and entails a comprehensive systematization of effects; and what is the result of its application for the Russian UES under the existing limitations of data?

2. Technical, Economic and Non-Economic Smart Grid Effects

Functional changes resulting from Smart Power System development are connected with technical and economic effects according to the elaborated system of Smart Grid effects. This system implies the direct link between changes in energy system and its structural subsystems performance characteristics, technical effects, and their economic evaluation. Existing classifications of Smart Grid effects do not interrelate these stages on the way of the cost-benefit analysis, and therefore cannot provide the foundation for correct estimation (EPRI 2010; WV SGIP, 2009).

In general, when conducting analysis of expected effects, it is necessary to take into consideration the fact that creation of the smart power system leads not only to simple quantitative increase of producing potential of the power system. Conversely, it changes existing and creates new technical properties in its structural subsystems (electricity generation, transmission, distribution or consumption) that are intended to change their functionality as follows:

- Increase in consumer load control abilities
- Possibilities to establish vibrant double-side interaction between the power system and consumers with distributed generation and/or energy storage sources
- Improved observability of the state of generation units, T&D lines and substations
- Automation and remote control of technical means in transmission, distribution and electricity consumption metering
- Real-time control of consumption profile, T&D grid operation modes and power system itself
- Enhanced monitoring and equipment diagnostics, with equipment working uninterruptedly
- High damage and accident sustainability, low accident coefficients
- More compact technical decisions and increased equipment life cycle

The proposed system of Smart Grid effects is schematically represented in Figure 1.

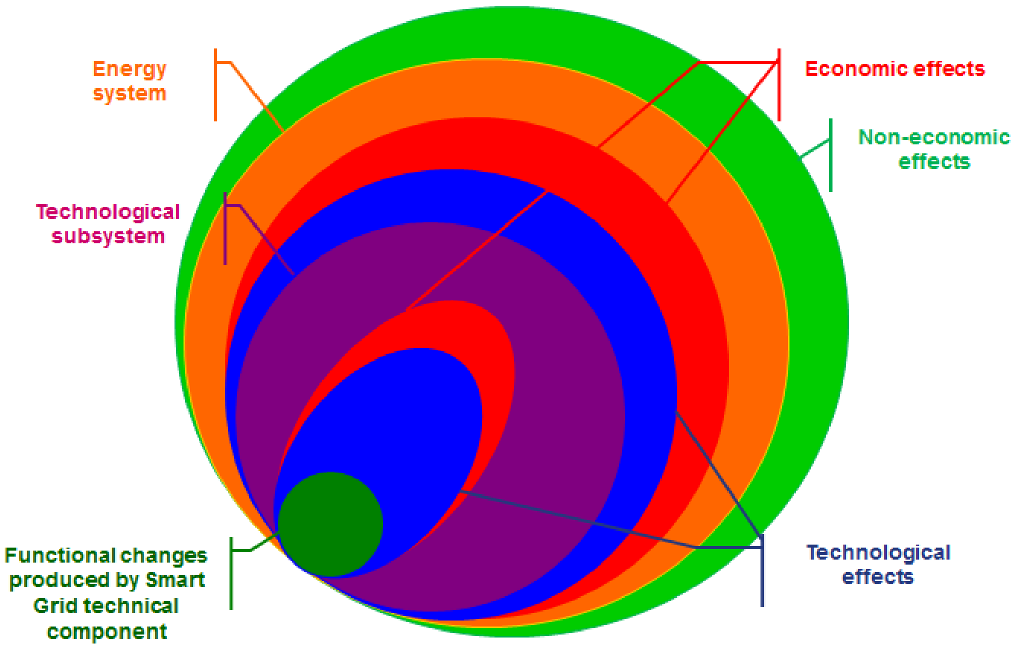

Figure 1. The system of Smart Grid effects

System technical effects and **local technical effects** as well as their characteristics are determined by functionality (technical properties) changes. These effects reflect a degree of change in the performance characteristics of the power system itself and its structural subsystems.

The first type of technical effects is local. It means that changes of technical properties in a certain subsystem caused by Smart Grid elements introduction will result in changes in performance characteristics of this subsystem only. For instance, automation and remote control of grid elements may reduce the need for maintenance personnel; volume and duration of network maintenance may be decreased with the improved observability and real-time monitoring of lines and substation operation parameters.

The second type of technical effects emerges on the system level. It means that Smart Grid elements introduction in one part of the technological electricity supply chain and subsequent changes of performance characteristic in this subsystem simultaneously lead to changes in technical properties and performance characteristics in other subsystems and in the whole power system. In particular, daily load transfer and peak shaving caused by consumers demand smart management is a system effect; it leads to a proportional reduction in capacity additions to meet the demand and a normative capacity margin requirement. Enhanced smart control over transmission and distribution capacity and operation modes also causes the system effect of better optimization of power plants operation modes and leads to the decrease in new generating capacities addition.[*]

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[*] In cases of elimination of congestion when the grid-constrained generation capacities become unlocked for the power system

Finance estimation of technical effects determines **direct economic effects (or benefits)**, emerging in separate subsystems (local effects) and in the whole system (system effects). One of Smart Grid’s most crucial properties is that it provides more effective utilization of existing producing potential in electric power industry. It also ensures a lower physical growth of the power system to achieve the same target balance requirements, system reliability and meet final supply reliability criteria. Therefore, direct **economic effects** are perceived as reduction in costs of power system operation and development.

The first type of economic effects is local. These effects are mainly defined by local technical effects, emerging in one structural subsystem of the power system. An example of such effects is T&D operational cost reduction caused by staff size reduction, decrease in maintenance volume and duration caused by remote monitoring and control, line condition monitoring, automated control of transmitting, distributing and metering equipment.

Other economic effects are **system effects** by nature, they are produced as a result of a joint impact made by system technical effects (e.g., reduction of generating capacities requirements), including:

- Reduction of capital investments in generating capacity additions of “system-scale” power plants caused by the reduction of peak load, final electricity consumption, distributed generation development, capacity margin requirements and increase in balancing power flows (as a result of smart T&D flow control);
- Reduction of capital investments in additional increase of transmission and distribution grid capacity due to more efficient monitoring and control of existing power lines, reaching positive results from consumers demand management and distributed generation development, which reduce reserve requirements for the grid;
- Reduction in fuel costs as a result of optimized utilization of generating capacities, integration of distributed energy generation sources into the system and gross electricity consumption decrease (including grid losses and self-consumption at the power plants).

Along with the previously considered effects, appearing in the electricity supply chain, reliability improvement and power supply efficiency impact on consumers are of crucial importance in a smart power system.

1) Finance evaluation of technological effects, affecting system and power supply reliability for various categories of customers, as well as the quality of supplied power, serves to estimate increase of avoided economic losses caused by physical constraints or poor quality of power supply. Quantitative estimation of these effects is made by modeling of power system operation conditions in normal and accidental modes with static and dynamic stability parameters. It requires calculation of reliability and quality indices, as well as estimation of

corresponding expecting unserved load volumes, differentiated by disrupt service duration. Final finance evaluation of consumer economic effects includes forecasted specific values of consumer avoided losses for various service disruption types.

2) Consumer price effect is caused by relative electric supply cost reduction as a result of emerging new opportunities, forms of competitive trading in the smart power system and infrastructural (grid and dispatch) tariff price component optimization. Quantitative measurement of the price effect is based on price dynamics modeling when carrying on different forms of both wholesale and local competitive trading, with regard to the rising demand elasticity on account of prosumers' active participation in the market (pic. 1). Economic competition between centralized electricity supply sources and distributed generation, as well as transmission and distribution services cost reduction are becoming possible due to smart grid control technologies.

Additional economic effect from active consumer (or prosumer) participation in ancillary services market should be considered too. Extension of technical ability of prosumers to actively participate in the system dispatching provides opportunities for the additional revenues from supply of these ancillary services (Fig. 2).

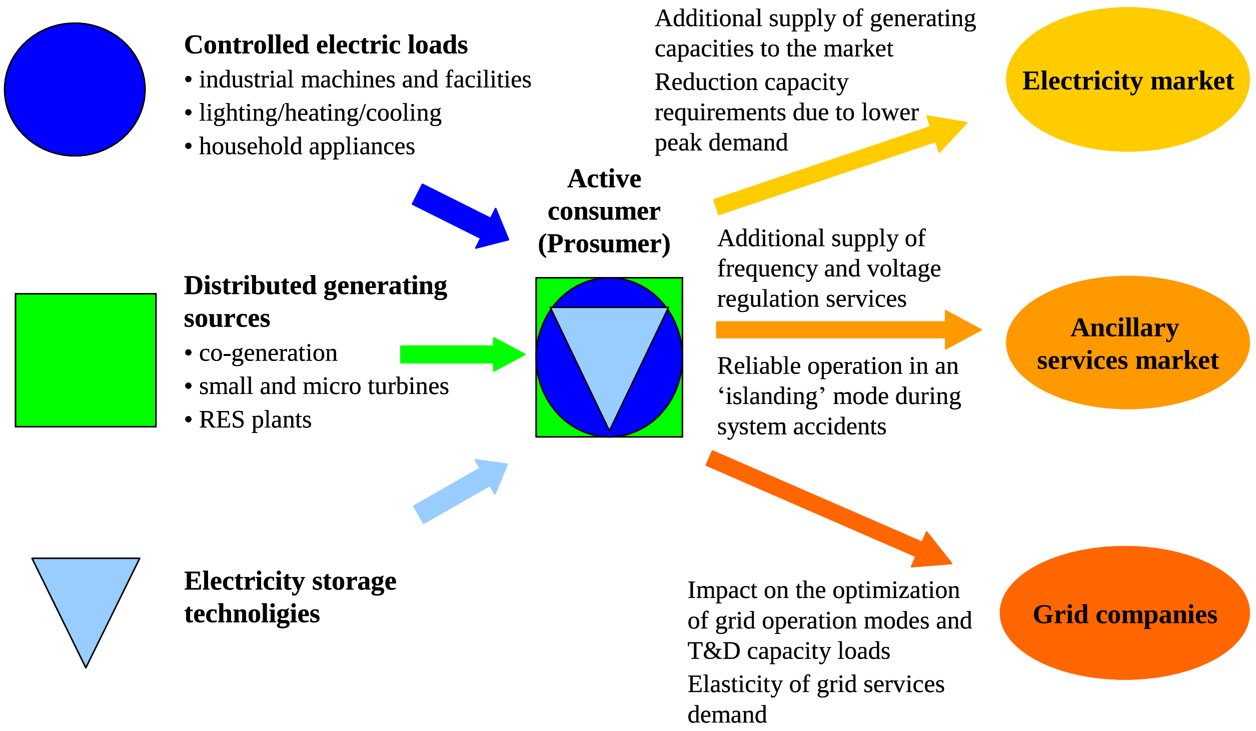

Figure 2. Main technological components of an active consumer (prosumer) and its contribution in demand elasticity increase at competitive electricity and ancillary services markets.

Experience in development of Smart Grid in different countries shows that its implementation should be considered not only as a challenging task for power engineers. To achieve this goal means to overcome certain technical, managerial and economic problems in the electric power industry, and the corresponding change therefore will produce a range of **non-economic effects** (EPRI, 2011; WV SGIP, 2009).

These effects demonstrate to what extent smart power system creation complies with social and economic requirements for new power supply standards. These effects should become a part of detailed Smart Grid development feasibility evaluation, complementing major technical and direct economic effects in the power sector and on the consumer side. The following effects can be defined as the most significant:

1) Reduction of environmental impact, including pollutants emission, greenhouse gases, electromagnetic radiation, alienable areas.

2) Innovative impetus for economy provided by the large-scale demand for R&D works in power engineering and electrical engineering, as well as the demand for informational and communicational technologies.

3) Increase in energy security as a result of supply reliability improvement due to grid control automation, distributed generation sources, electricity storage and microgrids development, which provide opportunities for prompt switching of consumers to autonomous energy supply in case of system accidents.

4) Improvement in market integration and enhanced competition due to flexibility of grid operation, transmission capacity and power flow control, smart metering systems development, transition to real-time pricing and active, two-way interaction between consumers and an energy system.

5) Increase in labor productivity and safety owing to automated remote control systems development, introduction of technical means with low accident index and increased life cycle.

Like direct economic effects, non-economic effects are determined by functional changes in structural subsystems of SPS. These effects also follow “basic” technical effects caused by introduction of new power system functionality. Almost all non-economic effects can be quantitatively evaluated, but their subsequent precise finance estimation is not always possible or may be performed only with a great deal of uncertainty. That is why it is reasonable to consider direct economic effects as main benefits in a smart power system feasibility study framework. Expert estimations of external effects can be used as constraining (narrowing) conditions.

The complete list of all effects is in Annex A.

3. General Methodological Foundation of Smart Power System Cost-Benefit Assessment

Economic assessment of SPS developed both nation-wide or region-wide should be based on the same basic methodological principles as those used for any investment planning in electric power industry. These principles imply that:

- Required capital costs of the program implementation correlate with the expected benefits. These benefits (economic effects) are increased revenues or savings of power system operation and development costs;
- Costs and benefits from the innovative ("smart") modernization of a power system are quantitatively estimated as a difference between performance and financial parameters describing two scenarios: "business as usual" (without SPS, based on the conventional technologies) and innovative (with SPS, based on smart technologies).
- Qualitative (or quantitative if appropriate methodology and information are available) estimation of non-economic effects, produced by Smart Grid. This evaluation is carried out with respect to the above mentioned power system development scenarios.

The variety of technological effects accompanying the transition to Smart Power System makes their quantitative evaluation be a multidimensional and multilevel challenge. The cumulative effect is formed by the separate local and system effects, produced by many types of smart technical equipment and control systems integrated into SPS. However, the volume of cumulative effect is not equal to the simple sum of the separate effects: different combinations of SPS elements are characterized by various levels of their synergy and mutual enforcement and/or compensation.

The variety of smart technical and control elements, their possible combinations and interaction in a smart power system requires a special approach to cost-benefit assessment based on the multi-stage optimization problem (Fig. 3). The proposed steps of SPS feasibility study were elaborated by the authors as a result of the analysis of existing experience in smart grid economic assessment, power system design and planning from the point of general methodology of system energy studies and forecasts.

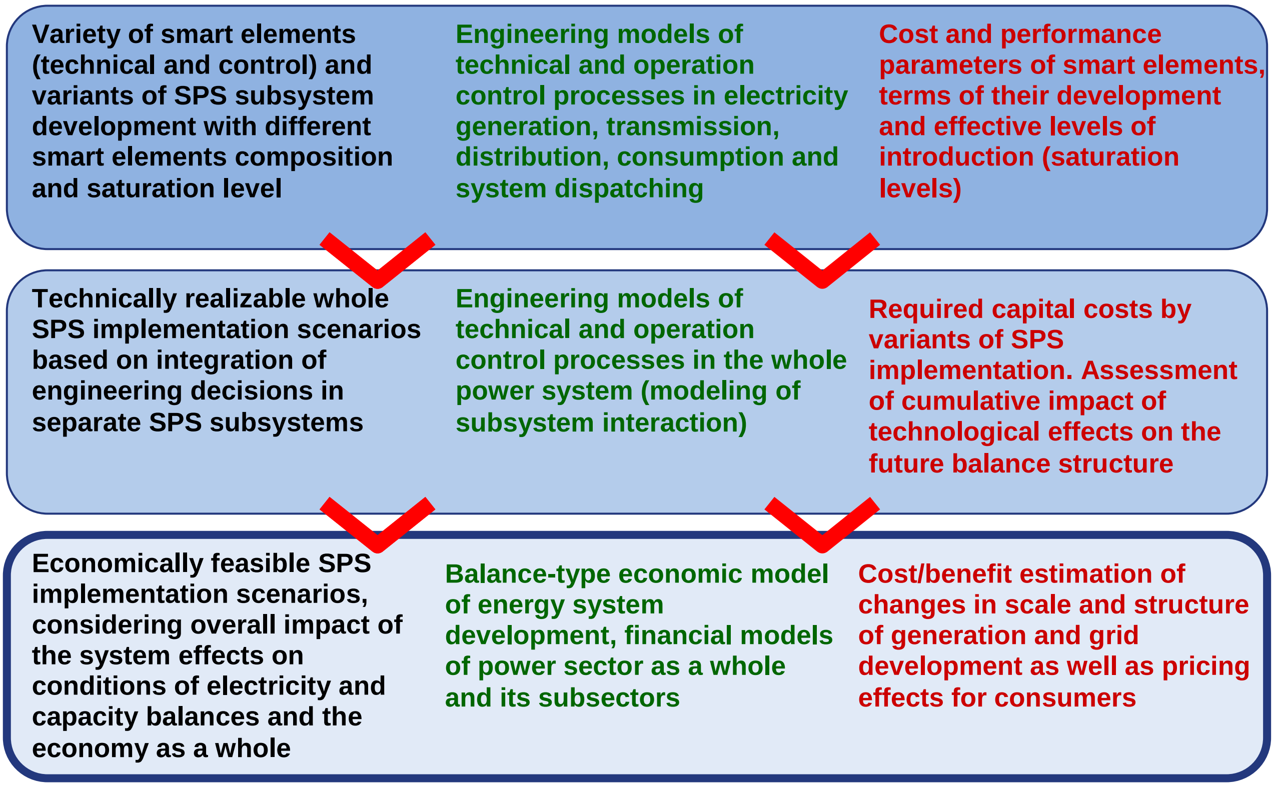

Figure 3. The stages of SPS feasibility study and cost-benefit assessment

1) The first stage begins with the elaboration and evaluation of alternative scenarios for development and "smartening" of separate electric power sector structural subsystems. These scenarios for each subsystem are differentiated by a composition of smart technical elements and control systems and their saturation level in the future SPS. These are the examples of such alternative scenarios:

- in electricity production – variants of distributed generation development, different storage technologies development;

- in electricity transmission – variants of high voltage grid development with various combinations of new technologies (FACTS, HVDC, etc.) accompanied by simultaneous increase in targeted levels of system reliability, grid observability and controllability, accidents preventing and mitigation, reduction in volumes, duration and costs of their elimination;

- in electricity distribution – variants of the infrastructure development with various combinations of smart grid elements used in lines and substations (possibly, with additional voltage levels and aerial/cable power lines types specification, if necessary), connected with automation systems as well as monitoring and management systems, providing targeted levels of power supply reliability, assets usage optimization, grid losses reduction;

- in electricity consumption – variants of demand and load management programs for various consumer categories. These programs combine technological changes with progress in metering systems and electricity storage, as well as alternatives of local generation development (renewables, micro CHP, electric vehicles), and are aimed at formation of different prosumer types who will participate in electricity and ancillary service markets in the two-way mode (consumption/ supply).

When elaborating on variants of structural subsystems' "smartening" (in generation, transmission, distribution, consumption) the following aspects should be defined:

- Technical specifications, performance and economic characteristics of separate SPS elements; expected period of pilot implementation, mass production and rational scale of introduction (saturation level);
- Functional changes in the subsystem (changes in existing or emergence of new technical properties), based on initial performance characteristics of the new technical and control elements and taking into account their superposition/synergy after their joint implementation;
- Local technical effects (changes in producing parameters) in the subsystem as a result of its functionality modification;
- Local direct economic effects (changes in capital investments, operation costs, decrease in consumer economic losses and ecological damage), caused by local technical effects;
- System technical effects, emerging in other structural subsystems as a result of functional changes in one subsystem.

The first stage tasks may be completed with the help of expert estimations and technical calculations for the separate smart technical elements and control systems, with subsequent transition towards the mathematical modeling. The models should cover technological and operation control processes in electricity generation, transmission, distribution, consumption and system dispatching. These mathematical models should be also adaptable and make room for further incorporation of different SPS elements.

2) On the second stage, the variants of Smart Grid development in the structural subsystems are combined in technically viable complete SPS implementation scenarios.

Firstly, for this purpose one should asses the technical affordability and possible hurdles that may prevent the structural subsystems development variants from integration in the complete SPS implementation scenarios.

Secondly, evaluation of the joint impact of the functional changes in separate structural subsystems should be performed for each designed SPS implementation scenario. Depending on the results of this evaluation the structure and characteristics of the local technical effects are revised in the all subsystems, along with the volume of local direct economic effects related to them.

Thirdly, integrated assessment of the system technical effects structure and characteristics is performed. Their aggregate impact on the future power system balance situation is supposed to lead to the changes in:

- Installed capacity requirements, including peak load, reserve margin, volumes of unavailable generating capacity;
- Gross electricity demand, including final demand and transmission and distribution losses;
- Limits on the existing and new transmission capacities for the intersystem balance capacity flows;
- Scales and modes of distributed generation involvement in electricity and capacity balances.

The models of integrated technical and dispatching processes in the whole power system serve as tools to achieve the goals set in the second stage. These models should simulate basic (technical, control, informational, etc.) interactions among end users (including distributed generation and local grids), transmission and distribution grids and large-scale generation.

3) Full-scale optimization of the alternative SPS implementation scenarios is performed in the third stage. Here the overall impact of the system technical effects on conditions of electricity and capacity balances in the long-term prospects being taken into consideration. Then optimization results are compared with “business as usual” scenario results (without SPS and based on the conventional technologies). The comparison makes it possible to obtain an aggregated picture of changes in power system performance characteristics for each SPS scenario development, including evaluation of:

- capacity additions in generation and grid (for intersystem power exchange enforcement and supply from new power plants);
- electricity production volumes and capacity factors of various power plants types;
- fossil fuel consumption and greenhouse gases and other polluting emissions.

And when the listed changes are evaluated, one can go on to measure the total system economic effects from SPS implementation, including necessary generation and grids capital investments and operation costs (including fuel costs).

System economic effects are complemented by the local economic effects, emerging in structural subsystems as a result of the local technological effects.

Total direct economic effect (adding up to the sum of the local and system effects) and its components (capital, fixed operation and maintenance and fuel costs) allow assuming electricity price change for end users at the final stage.

Final evaluation of the system economic effects can be performed with balance-type mathematical model of energy system development. The model should provide dynamic (for the whole forecasting period) optimization of the capacity and electricity balances in the power system on the regional basis (to evaluate the SPS effects in transmission capacities). The regional centralized heat supply balances and fuel supply balances for power plants are also important to include in the model.

To evaluate price effects SPS implementation had on consumers, specialized financial and economic models of electric power industry and its separate sectors are used. These models are designed to adjust all the necessary costs and finance sources, and validate reasonable consumer price level and transmission and distribution tariffs.

The result of the final stage is a quantitative estimation and the best scenario(s) SPS implementation dynamics, maximizing the total direct economic effect.

Additional step of the feasibility study can include non-economic effects evaluation for the selected SPS scenarios, if the relevant methodology is available. Some of the effects (e.g. ecological impact) may be considered as additional constraints for optimization.

4. Application of the Suggested Methodological Framework of Smart Power System Effects' Evaluation to Russian Energy System

Russian Energy System brief characteristics

Before the presentation of the applied procedure and results of SPS system effects evaluation, it is important to give a brief review of the Russian Unified Energy System characteristics, as far as its data was used for testing of the approach.

Russia is in the TOP-5 of countries in the world with the largest electricity generation volumes and installed capacity. At the same time Russian power system is characterized by the range of technological features, which are supposed to significantly affect the choice of priorities, scale, speed of progress and as a result – costs and benefits of Smart Grid implementation.

Firstly, last century the Unified Power System (UPS) was created in Russia. It is effectively functioning at present and combines more than 500 power stations, and transmission grids operating on a synchronic mode within the territory that is 5000 km long. Some technical means and dispatch methods that are already used in the Russian UPS can be percieved as smart power system components due to features present in them. That is why Smart Grid concept is widely discussed in Russia in the context of smart power systems implementation on a local and national scale.

Secondly, Russian electric power system is characterized by extremely high amortization level and low energy efficiency. In 2010 the age of about 40% generating capacities exceeded 40 years; the average fuel efficiency amounted to 25-35%, for gas-fired stations – about 38%. Over 27% transmission and 7% distribution grids are over 40 years old; transmission and distribution losses reach 12%. Therefore, smart power system implementation in Russia is primarily considered in terms of full-scale technical industry re-equipment.

Thirdly, Russia has an extremely low transmission and distribution grid density that requires special attention to the new power flow and capacity reserves control methods. Thus, "N-1" parameter is not always met when new power plants or consumers are connected to grid, let alone stricter normatives "N-2" and others. Moreover, electricity load density and grid quality strikingly differs in megapolises (Moscow, St.Petesburg, Kazan – 13 cities with population more than 1 mln people) and in the territories with highly distributed and remote loads; as a result they require principally different solutions for power grid intellectualization.

Finally, high grid tariffs (including the connection fee) cause industrial and commercial consumers to develop distributed generation actively. It is worth mentioning that due to relatively low fuel pricing fossil fuel power plants are preferable in the majority of regions, and the majority of distributed generators are mini and micro gas-fired CHP. Centralized heat supply systems are widespread and traditional in Russia, this is why Smart Grid development should cover both electric and heat supply systems, including those based on distributed co-generation sources.

Quantitative evaluation of the Russian UPS balance changes related to Smart Power System implementation

With regard to the outcomes expected in the Russian UPS as a result of the SPS implementation we considered the following set of system technological effects, which greatly influence demand/supply balance conditions:

- load management effects, leading to changes in electricity consumption profiles (decrease in peak load and flattening of daily load curve), which often are accompanied by total demand decrease;
- electricity T&D losses control effects, containing: non-load losses reduction due to new wire types and substation equipment introduction, load-related losses reduction caused by transition to smart grid operation control, and change in electricity consumption regimes due to smart demand response;
- transmission and distribution capacity control effects, increasing upper limits of balancing capacity flows due to introduction of FACTS technologies and new automated monitoring systems of grid static stability;

- effects resulting from optimization of generation capacities operation and development. These effects are associated with efficient combination of bulk and distributed generation accompanied by the same (in some cases – decreasing) relative to peak load capacity margin in the power system. One of the important effects mentioned is large-scale distributed generation integration and improvements in power flows obtained from renewables with intermittent production profile;
- effects resulting from improved reliability and quality of supply control: decrease in frequency and duration of accidents, leading to customer supply curtailment or unsuitable quality, and, consequently – to reduction of consumer direct economic losses.

To conduct the estimation of direct system technical and economic effects in the Russian UPS resulting from implementation of the smart power system concept more than 50 pilot projects and complex Smart Grid development programs worldwide, either being finalized or under implementation in different countries, were analyzed to find out their expected or obtained results. Only about 30% of the projects had published information concerning quantitative results, more expected than obtained.

Currently many innovative smart technologies are on the level of R&D studies, and there is no practice of their integration and combination with smart control systems. These factors determine extremely high uncertainty of expected effects from Smart Grid elements introduction. However, the obtained summary of target values and the first results of pilot projects in the world let us clarify the scope of possible effects for the Russian UPS, which were preliminary estimated by Makarov and Dorofeev before (Dorofeev, Makarov, 2009). Current estimations have provided a baseline for the main Russian strategic document "Concept of Smart Power System with Active Adaptive Network" (Volkova, Bushuev, Veselov, 2012).

The final parameters of the expected changes in balance conditions in the first and second stages of SPS implementation are presented in table 1. They reflect low and average values obtained in the analyzed pilot projects and programs. Expectedly, SPS project will be ¼ complete in the first stage.

Table 1

Expected changes in balance conditions in the Russian UPS with implementation of Smart Power System concept, %

	Smart Grid pilot projects	Target parameters of Smart Grid in Russian UES	
		1st stage	2nd stage
Decrease in forecasted peak load	10-20	2,5	10
Decrease in electricity consumption	5-15	2	8
Decrease in grid losses, % from current	20-50	7,5	30
Decrease in **required** capacity margins	20-30	5	20

Increase in interconnector transmitting capacity	5-10	2,5	10

Joint impact of these technical effects entails quantitative changes in the Russian SPS balance parameters through the change in electricity and installed capacity demand.

Expected change in electricity demand can be determined by:

- Decrease in final consumption as a result of smart (active and adaptive) demand response;
- Decrease in electricity losses due to the introduction of new technical elements, providing non-load losses reduction, as well as smart power flow control systems introduction;

Change in total installed capacity requirement is estimated similarly, it is characterized by:

- Decrease in peak load as a result of smart demand response, and proportional decrease in generation capacity reserves;
- Decrease in the relative reserve margin volume due increase in power supply reliability. Bulk capacity reserves contribution to ensuring of standard reliability level is therefore can be reduced by alternative measures, applied in grid and/or at the consumer side (including distributed generation and electricity storage items).

It is important to note that joined influence of technical effects on future balance situation has a significant synergy. As a result, changes in electricity and capacity demand do not add up simply to a sum of effects listed above. Implementation of Smart Power System in the Russian UPS will lead to the installed capacity demand reduction by more than 10% and electricity consumption almost by 9% in comparison to "business as usual" (BAU) projected balance conditions (without SPS). Relative grid losses level will gradually decrease by 30%: from 12% to 10% in the first stage and 8% in the second. As picture 3 shows, capacity demand will decrease by 34 GW, electricity demand – by 140 TWh (relative to BAU scenario) in absolute terms.

Table 2

Quantitative estimation of changes in the Russian UPS balance conditions as a result of Smart Power System development (in comparison to "business as usual" scenario)

	1st stage	2nd stage
Installed capacity demand reduction, GW, including:	7.2	34.1
- Maximum load decrease as a result of demand management	4.8	23.4
- Margin reduction because of reliability increase and maximum decrease	2.4	10.8
Electricity demand reduction, billion kWh, including:	23.3	140.1
– End consumption reduction as a result of demand management	23.2	113.8
– Grid losses reduction due to new loss control technologies and consumption decrease	0.1	26.3

Quantitative evaluation of changes in the Russian UPS development parameters was performed by virtue of the linear optimization model EPOS, made by ERI RAS as a part of the integrated modeling complex for global and national energy sector forecasting (SCANER).

This model was invented by Russian researchers (Veselov et al., 2010) to enable the governmental and corporate stakeholders to choose among the strategies of generating capacity and intersystem links development in the Russian UPS in medium- and long-term prospect jointly with gas and coal industries development dynamics. Therefore the model serves as a tool for dynamic (for the whole forecasting period) optimization of the power sector, providing an optimized generation mix and required development of gas and coal extracting and transport systems. The modeling can be performed for national and regional energy balance formation.

EPOS combines mathematical description (in the form of linear programming task) of key technical and regional links within the electric power sector itself and intersectoral links with fuel industries. As Figure 3 demonstrates, the structural basis of the model is a system of regional balances of electricity, installed and rated capacity, centralized heat and main fuel types (gas, fuel oil, types of steam coal). Depending on the study purposes, representation of generating capacities can range from hundreds of generating units to limited (20-40) types of aggregated generating technologies. Limits on available capital expenses (depending on power plant types or generating companies) or CO_2 emission can be included in model if necessary.

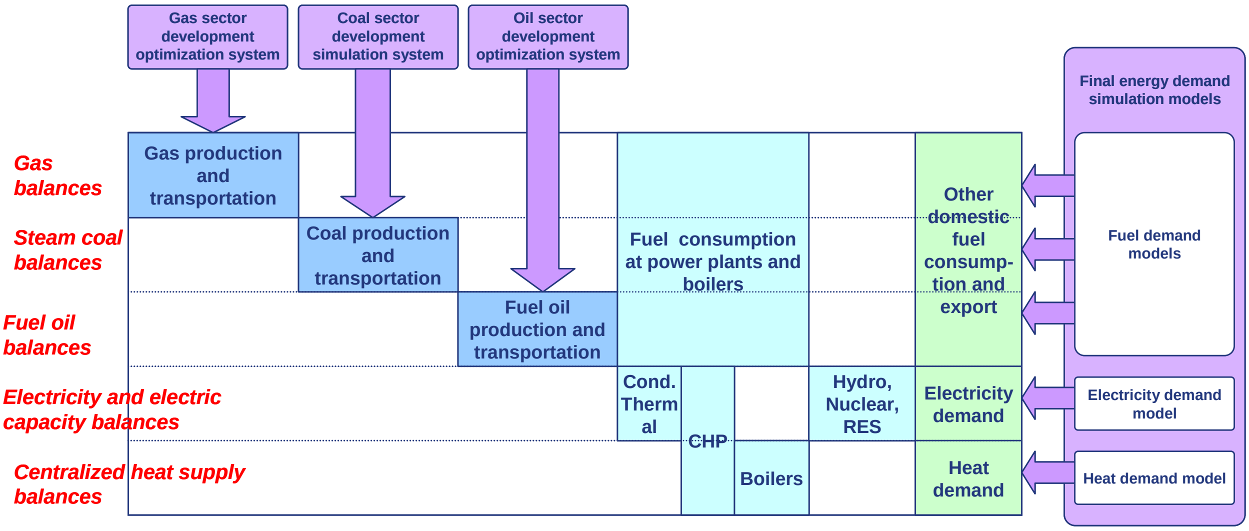

Fig 3. Structure of EPOS model for joint optimization of power sector and fuel industries' development, and its functional links with other parts of integrated modeling complex for global and national energy sector forecasting (SCANER)

EPOS optimization criterion adds up to a minimum of total discounted costs of:

- development and operation of the electric power sector (including centralized heat supply system), and fuel industries (gas and coal) in the planned period,

- operation of new objects built due to investment decisions in the following 10-15 years (the so called aftereffect period).

Social efficiency of the optimal scenarios of the power sector development predetermines optimal least-cost decision choice with perspective regional fuel balances being taken into consideration.

Modeling results show (table 3) that transition to innovative development of the Russian UPS on SPS basis will lead to the modified power sector structure in terms of the dynamics of installed capacity growth, types of capacity additions, electricity production and fuel consumption as follows:

- Balance conditions changes will lead to decrease in new capacity additions of thermal electric power plants by 25,8 GW (including 7 GW on CHPs); nuclear and hydro capacity additions will decrease less (by 4 and 4,4 GW, respectively);
- Grid capacity additions will be reduced too because of the reduced power plants additions and required lines for their integration as well as reduced intersystem links capacity extension to meet balancing needs. The rates of grid development to provide system reliability for large consumers or regions will slow down as far as reliability issues will be partially solved at the distribution level.
- Electricity consumption reduction will lead to slowdown in electricity production growth rates, primarily in thermal power plants. Production of condensing power plants will decrease by more than 80 TWh or 17 % till the end of the second stage of SPS implementation in comparison with BAU scenario. At the same time, capacity factor will increase almost for all thermal power plant types; this is also an important technical system effect;
- As a consequence of changes in the capacity and electricity production structure annual fossil fuel consumption in electric power industry will decrease by circa 19 million tons of oil equivalent or by 8% comparing to BAU scenario. Gas accounts for the major part of this fuel savings.

Table 3

Changes in the Russian UPS performance parameters with the implementation of SPS concept (in comparison to “business as usual” scenario)

	1st stage	2nd stage
Reduction of installed capacity, GW	-7.8	-34.1
Hydro and pump-storage and RES	-1.7	-4.4
Nuclear	-1.0	-4.0
Fossil CHP	-0.8	-7.0
Fossil condensing plants	-4.4	-18.8
Reduction of annual electricity production, TWh	-23.3	-140.1
Hydro and pump-storage and RES	-3.4	-10.8
Nuclear	-6.1	-29.0
Fossil CHP	-0.9	-19.6
Fossil condensing plants	-12.9	-80.8
Reduction of fuel consumption, Mtoe	-4.7	-27.6
Gas	-4.1	-25.8
Fuel oil	0.1	0.0
Coal	-0.7	-1.5
Other (incl. biofuel)	0.0	-0.3

Drawing a conclusion, Smart Power System implementation results exceed technological power sector modernization (its grid complex, first of all). In comparison with “business as usual” scenario transition to SPS gives an opportunity to solve the problem of power system development by **more intensive exploitation** of industry productive potential as well as consumer sources. This approach therefore reduces **extensive expanding** of generating and grid capacities which may be required to meet the balance reliability and end users electricity supply quality targeted requirements.

Smart Grid Cost-Benefit Estimations for the Russian UES

Total economic effects were evaluated on the basis of the estimated changes in the Russian Unified Power System performance parameters. These effects are mentioned above and related to demand and load management, control of grid losses, operation modes and transmission capacities, bulk and distributed generation, power supply reliability and quality (Veselov, Fedosova, 2014). Financially, these effects manifest themselves in the decrease in:

- capital expenses on generating capacity additions (due to reduced capacity requirements);

- capital expenses on T&D lines and substations modernization and new construction (due to increased grid transmitting capabilities and reduced peak load);

- operational expenditures in T&D grids and generation, first of all – fuel expenditures arising due to changes in thermal generation additions and capacity factors.

Compared to BAU scenario of the Russian UPS development, total economic effect produced by Smart Power System implementation can amount to about 3,5 trillion RUR by the end of the second stage of implementation (table 4).

Reduction of capital expenditures which results from decrease in generating capacity additions and grid development for their integration is the most significant system economic effect. The impact of such reduction can amount to almost 2 trillion RUR (in 2010 prices) by the end of the second stage of implementation. [2]

Table 4

Economic effects of Smart Power System implementation in the Russian UPS

	The end of the first stage	**The end of the second stage**
Reduction of capacity additions, GW	7.8	34.1
Reduction of fuel consumption, Mtoe	3.3	121.6
Reduction of GHG emission, Mt CO_2	8.4	297.6
Total direct economic benefits, USD 2010 billion	**23.7**	**114.2**
Capital costs savings	22.6	64.7
Power plants	*20.3*	*57.4*
Reinforcement of intersystem congestions and integration of new generation capacities	*2.3*	*7.3*
Reduction of fixed O&M costs	0.6	18.5
Reduction of fuel costs	0.4	25.0
Reduction of carbon costs	0.2	5.9

The second largest effect is the reduced fuel costs due to reduced electricity generation and changes in its structure, totaling to 750 billion RUR by the end of the second stage of implementation.

Reduction of power sector fixed operation and maintenance costs made possible due to reduced generation and grid capacity additions is estimated at 560 billion RUR by the end of the second stage of implementation.

Additional effect from fuel saving can be achieved provided carbon pricing policy is taken into consideration. Even at a comparatively low CO_2 emission price near 600 RUR per ton additional savings equals 180 billion RUR.

Aside from the direct economic effect in the power sector, reduction of consumers' costs is quite significant. It is caused by prevention of consumers economic losses as a result of reliability and quality of power supply improvements, and by the end of the second stage of implementation this effect is estimated to equal 1.3 trillion RUR.

Operation and carbon cost savings in the period after the 2nd stage of SPS implementation will increase economic impact by about 1-1.5 trillion RUR each five years, which adds up to 2-3 trillion RUR for the considered 10-year period of aftereffect.

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[2] Hereinafter financial estimations are given in RUR 2010.

Obviously, estimated benefits should be compared with investments required for large-scale SPS introduction for consumers, distribution grid, transmission system, generation, technical and commercial system dispatching areas.

Due to the current absence of holistic vision and engineering design of future Smart Power System in Russia, preliminary estimation of investment requirements was carried out by analog method (table 5). Standard cost parameters of smart technical means and control systems taken in a similar system-wide Smart Grid project in the USA, conducted by EPRI in 2011 (EPRI, 2011), were taken as a basis.

Table 5
Total capital expenditures on Smart Grid development in Russia and the USA

	Capital costs	
	Minimum estimation	Maximum estimation
US Smart Power System development (by EPRI) – total, USD 2010 billion	340	475
- Transmission lines and substations	82	90
- Distribution grid	235	340
- Consumers	23	45
Russia's Smart Power System development, – total, USD 2010 billion	78	106

Taking into account the Russian UPS technical specific features, preliminary value of capital expenditures for Smart Power System implementation based on deep T&D grid infrastructure modernization, equipment on the consumer side and dispatch systems upgrade, can total to 2.4 – 3.2 trillion RUR. Comparison of undiscounted values of direct economic effects and required capital costs for Smart Power System implementation (Fig. 4) shows that benefits from SPS project realization in the Russian UPS will outweigh all the necessary costs already by the end of the second stage of implementation. Generally, taking into account the aftereffects in the power sector and on the consumer side, but not considering non-economic effects, SPS implementation benefits outweigh required costs in the ratio 2.5-3.5 to 1.

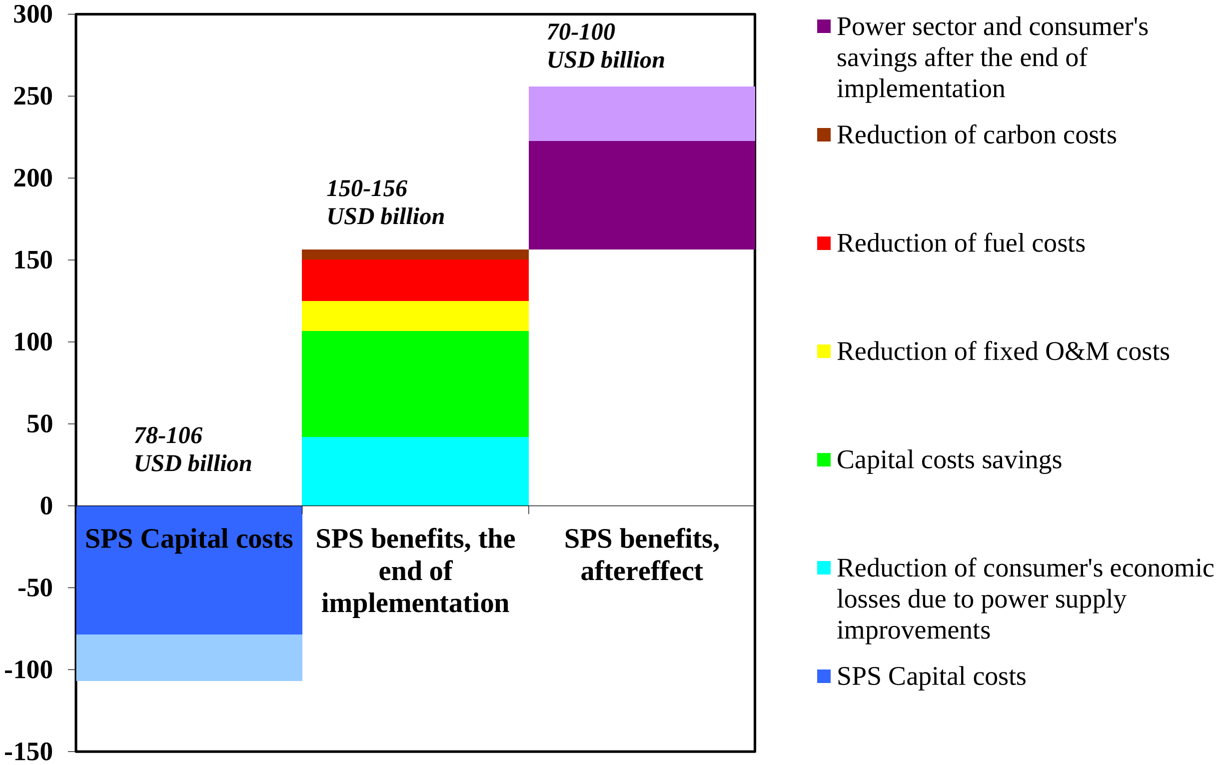

Fig. 4. Costs and benefits from Smart Power System implementation in the Russian UPS, USD billion 2010

5. Conclusion

The case of Smart Grid conceptual and strategic documents elaboration in Russia demonstrates the importance of complex, system approach to Smart Power Systems design and implementation.

At the same time, without any doubt, the most important research and practical problem is qualitative structuring and quantitative assessment of various technical and economic effects, emerging in the power system and on the consumer side, as well as external effects for the society and economy. Relevance of the quantitative cost-benefit estimation is basic for the feasibility study of long-term risky investments in Smart Grid both by government and private companies.

The presented systematization of smart power system effects implies the existence of two levels on which they emerge (system and local), two types of quantitative effects (technical and economic, the latter are caused by the former) and a category of non-economic effects. This approach is useful for cost-benefit assessment on a system level since it avoids double count, introduces the link between smart power system effects and is comprehensive. The developed systematization is applied in the presented methodological approach to smart power system's feasibility study, having three main steps: 1) development of scenarios of smart power system implementation; 2) selection of the technically viable scenarios and assessment of technological effects; 3) optimization and assessment of economic effects. The approach's application therefore demands the access to detailed information about smart grid technologies' properties, compatibility and efficiency. Currently such kind of data is on the stage of collection from pilot projects, therefore, only the part of the proposed approach has been tested using optimization modeling.

It is shown that Smart Grid development produces significant system technical effects, which will seriously influence the future demand and supply balance and ensure the reduction in capital and operational costs of power sector development in the end. The changes in balance situation in demanded capacity and electricity will amount to about 10% reduction for the Russian UPS by the end of SPS implementation.

These effects can be quantitatively evaluated not only on the expert level, but also by means of the formal mathematical modeling tools. They substantially increase the assessment reliability and make it possible to imitate various SPS implementation scenarios, estimate the synergy of technical effects from new smart technical means and control systems.

With regard to Russia, direct economic effects in the power sector and consumer supply reliability will exceed costs of SPS implementation 2.5 - 3.5 times. However, this ratio may surge provided non-economic effects, including innovative impetus for the additional economic growth, are added to the estimate.

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Appendix A

Table A1

The system of Smart Grid effects

Functional changes	Subsystem		Energy system		Non-economic benefits
	Technological benefits	Economic benefits	Technological benefits	Economic benefits	
Electricity consumers (including distributed generation)					– CO2 emission reduction; – enhanced energy safety; – increase in labor safety and automation; – better circumstances for economic integration and competition; – innovative impulse for economy
– on-line demand management; – new electric supply services, price/reliability differentiation; – electric storage; – active end-users' generation participation in electricity market; – real-time informational exchange with the energy system; – additional sources of active and reactive power in the energy system; – opportunity to work in a parallel and an island modes	– decrease in maximum electricity consumption – shaving of daily load graph	– reduction in consumers' costs – reduction in consumer losses from supply disturbances	– decrease in the system load maximum – grid and power plants load modes optimisation – grid losses decrease – decrease in capacity margins volume and allocation – decrease in the demand for intra-day generating capacity unloading – decrease in the requirement for grid capacity margins in public networks	– decrease in capital costs for new generating capacity installation – decrease in power plants fuel costs – decrease in capital costs for public network development	
Electricity transmission and distribution					
– broader opportunities for transmission capacity and load optimization – remote control of devices – improvement in assets observability	– decrease of transmission and distribution losses – increase in transmitting capacity – reduction of equipment failures	– decrease in capital costs for grid development – decrease in expenditures for transmission losses – decrease in repair	– decrease in electricity production – optimization of generating capacity load modes – decrease in generating capacity	– decrease in power plants fuel costs – decrease in capital costs for new generating capacity installation – decrease in consumer losses from electricity	

Functional changes	Subsystem		Energy system		Non-economic benefits
	Technological benefits	Economic benefits	Technological benefits	Economic benefits	
and accuracy of measurements – space-saving technical solutions – increase in quality of equipment monitoring and diagnostics – grid functioning automation level increase – higher resistance to failures – simplicity and quickness of recovery from failures – longer equipment life	number – reduction in maintenance duration – staff number reduction – decrease of all types of blackouts – decrease of landtakes for grid objects	and maintenance costs – decrease in labor costs – decrease in operating costs for new equipment	margins – increase in electric supply reliability – increase in electric supply quality – enhancement of electricity market price zones integration	shortage and poor quality – average wholesale price reduction because of less price differentiation by market zones	
Electricity generation					
– increase in regulation range of base-load and mobile generators – increase in quality of equipment monitoring and diagnostics – real-time interaction with active grid control elements	– generation load optimization taking into account generation capacity margins and available transmission capacity – reduction of equipment failures number – reduction in maintenance duration	– decrease in repair and maintenance costs – decrease in power plants fuel costs			

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