PROFITABILITY OF SMART GRID SOLUTIONS APPLIED IN POWER GRID

by

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The idea of smart grid solution has been developing for years, as a complete solution for the power utility, consisting of different advanced technologies aimed at improving the efficiency of operation. The trend of using various smart systems (such as implementation of energy management systems, grid automation systems, advanced metering infrastructure, smart power equipment, distributed energy resources, demand response systems, etc.) continues to develop. In this respect, emerging technologies (energy storages, electrical vehicles or distributed generators) become integrated in distribution networks and systems. Nowadays, the idea of smart grid solution becomes more realistic owing to full integration of all advanced operation technologies (OT) within IT environment, providing the complete utility digitalization (IT/OT integration). The overview of smart grid solutions, estimation of investments, operation costs and possible benefits are presented in this article, with discusison about profitability of such systems.

Key words*: smart grid, electricity distribution, distribution management systems*

Introduction

Power utilities apply various advanced technologies for control of different grid components, such as transmission, generation or distribution. This paper is focused on smart grid solutions applied in distribution utilities. Smart grid solution (SGS), considered as different advanced technologies aimed at improving the efficiency of operation, should significantly improve reliability, quality and efficiency of power delivery and reduce costs of power network operation. The challenge is quantification of benefits provided by SGS and comparison with related costs, to estimate the real profitability of such investments. Such research was conducted on numerous real cases [1-5] to evaluate benefits and costs of SGS applied in electricity distribution networks (EDN). The evaluation of SGS benefits and costs, as well as recent results are presented in this article.

Nowadays, utilities have the following major expectations of SGS:

– Improve performance indices of the grid operation, as they are often regulated by regulators,
– Improve reliability indices of the operation, also often regulated by regulators,
– Improve customer services, as they directly affect market position in case of deregulated markets, where customers may choose the provider.

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The SGS encompass different technologies aimed to improve efficiency of EDN operation, as presented in fig. 1, and they can be grouped in the following areas:
- Smart network operation: implementation of distribution automation systems (DAS) with centralized grid control and smart power equipment,
- Smart metering: implementation of advanced metering infrastructure (AMI) with automated (remote) meter reading (AMR), and meter data management (MDM),
- Smart consumption: monitoring and optimal management and control of demand – demand response systems (DRS),
- Smart generation: monitoring and optimal management and control of distributed energy resources (DER),
- Smart devices: modeling of electrical vehicles, chargers of electrical vehicles and energy storage devices in the distribution network.

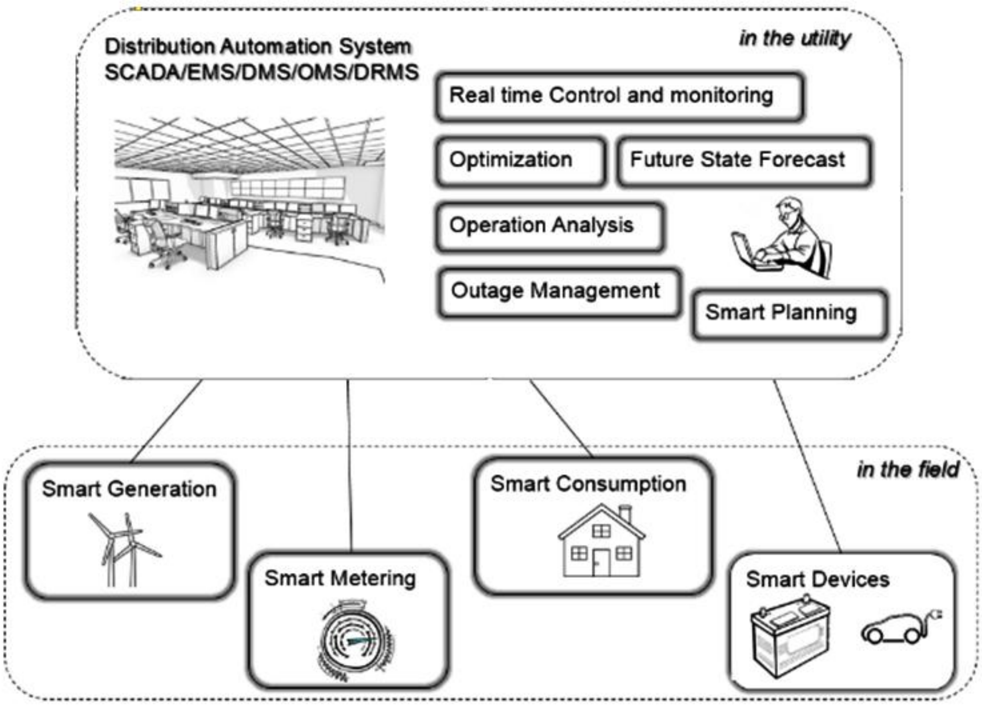

Figure 1. Smart grid technologies

The highest efficiency is achieved when all modules are integrated within one integral solution. DAS system in this case operates as the central *brain* of the entire SGS system, overviewing and managing all modules. The DAS systems typically include:
- Centralized system control software, including SCADA (Supervisory control and data acquisition system), DMS/EMS (distribution/energy management system), OMS (outage management system), operation analysis, forecast and planning, all integrated in one solution – advanced DMS (ADMS),
- Centralized system control hardware, including typically primary data center servers, disaster recovery data center servers and user workstations,
- Communication system to support high speed transfer of data over wide areas,

– Remotely controlled field power equipment in the grid (load breaking switches, fault indicators, voltage/capacitors regulators with motor drives), including communication subsystems (remote terminal units with radio or line communication modems).

The ADMS is the central intelligence of DAS providing the full network control, mathematical modeling and single graphical interface. The ADMS supports network visualization (schematic and geographical), network monitoring and control, access to comprehensive technical database, environments for real-time control and simulation studies, historical data access and storages, web technologies, as well as wide set of power analytical functions:

– Core functions for calculation of network operation state and topology (state estimation, power flow, topology analyzer, …), automatically triggered by system,
– Operation support functions for switching scheduling, issuing of commands, incident and work management, typically used by operators in every day network operation,
– Operation optimization functions for optimizing grid operation, power flow and voltages, typically used by engineers for short-term operation planning. Recently, these functions have become available in automatic mode likewise – working sequentially in a closed loop and automatically issuing commands to field equipment in real-time,
– Network analysis and reporting functions to analyze short-circuits, relay protection setting, contingency problems, equipment rating, harmonic pollution, and provide reports about outages, power losses, *etc.*, typically used by engineers in simulation mode,
– Outage management applications for management of faults in automated way (fault location, isolation and supply restoration – self-healing),
– Network Development functions for maintenance planning and long-term analysis of network design, construction and development, typically used by engineers in investment and planning departments,
– Web applications allowing web access to corporate clients on portable devices.

Smart metering implies AMI implementation with smart meters on customer side, communication with meters to upload data from meters, as well as modules for data processing (MDM), typically including the following modules:

– Smart meters – used for the measuring (recording) of consumption on customer side, storing of data in meter, supporting two-way communication to provide (upload) data and accept data requests and commanding signals,
– Communication network – used for data and signals transmission between meters and communication nodes, with different technologies used (power line carrier, private radio or wireless IP networks, private wire/fiber optic IP networks or public mobile providers),
– Network management software – AMI host system and meter data management system that manages data storage, pre-processing and analysis, to provide appropriate data to different users in utility (Billing system, ADMS, web services, *etc.*).

Smart consumption implies DRS technologies to *control* consumption of electric energy on demand (customer) side directly or indirectly, with consent of the customers and with their participation in a certain *demand response programs*. The DRS is aimed at reducing the power system peak load or the local network overload, without significant violation of supply quality. In this way, construction of new and expensive *peak-load* generators can be avoided with overall reduction of costs, as well as CO_2 pollution. The DRS typically consists of the following modules:

– Demand response management system (DRMS) is software applications which provide analysis of network operation and creates schedules for execution of DRS programs. Nor-

mally, such module is the part of ADMS, however, in some applications it is established as independent system,
- The DRS web portals, which manage the participation of customers, with their applications, signing in/contracts, tracking of DRS event results, compensations, *etc*.,
- The DRS master control system, which convert DRMS programs to execution signals (*e. g.* control signals to local devices in direct control systems or notifications to customers in indirect control systems),
- The DRS communication system (*e. g.* radio system, power network, AMI, private IP network or public mobile provider, *etc.*),
- The DRS local control devices (*e. g.* local PLC, home control systems, smart meters, load control switches, programmable communicating thermostats, *etc.*).

Smart generation implies technologies for DER monitoring, modeling, control and management (DERM). Analysis of the new DER connections and their impact on network operation is necessary and possible with DERM mathematical and control engines. Smart generation includes:
- The DER local control devices with remote communication,
- The DERM master system for remote monitoring and control,
- The DERM applications for DER analysis, protection setting, optimal dispatch and analysis of new DER connections.

Smart devices imply integration/modelling of electrical vehicles and energy storage devices in the distribution network within ADMS. The growing number of these devices and higher interest of both utilities and personal users imply the need to model these devices and account for their impact on the network operation. Furthermore, smart management and optimal utilization of their capacities can reduce unnecessary costs, avoid unexpected peaks and imbalances in the consumption.

Smart grid benefits

Smart grid solutions predict entire digital automation of distribution power networks, from the entry point on the transmission network to the customer side, with aim to improve reliability and efficiency of supply and reduce costs of operation. Benefits achieved with SGS implementation are comprehensive and the most important are listed below:
- Improved network reliability and operation in a real time,
- Reduction of outage time: self-healing sophisticated technologies, operating in manual and/or automatic mode, significantly reducing outage time to minimal values and improving reliability of power supply. In cases when utilities pay penalties for outages, this means direct savings for the utility,
- Reduction of operation and network construction costs: with higher utilization of existing/expensive power equipment and smart planning of new facilities or customer connections,
- Secured networks – the development of new technologies enable efficient identification and response to natural disasters and human intrusions,
- Optimal management of distributed generation production, by integrating DERM and DRS systems,
- Active customers - participating in demand response programs and having possibility to self-control their consumption,
- Optimizing power flow in the distribution network by controlling the impact of electrical vehicles, DER and energy storage devices.

Benefits, resulting from SGS implementation in distribution networks, are analyzed, quantified and compared with the market value of *electric energy annually injected into distribution network* (EEIA). Business models applied in electric sectors worldwide are different, from monopolies to fully deregulated open economies. Since utilities have different business models for generating revenue, benefits and costs will be compared with EEIA, as well known parameter in each utility [1, 2, 4].

The DAS benefits

The central intelligence of DAS is ADMS, which includes (mathematical) modeling of power network and set of calculation engines and algorithms to provide network operation optimization, incident management, analysis, reporting and long-term planning. ADMS calculation results are applied in field by SCADA and OMS modules, over communication and field execution systems, to achieve optimization and control targets. DAS benefits [4] can be differentiated as follows:

- Reduction of power losses: ADMS optimal network reconfiguration function applied in network operation may provide reduction of power losses [6-8]. Besides, ADMS Volt/Var will improve voltage quality and reduce losses [9-11], as well as energy audit will help in tracing and reducing non-technical losses. Co-ordinated implementation of ADMS results in network operation, which can be set in automated way nowadays, may bring 10-15% reduction of power losses, or benefit of approximately 0.5-1% EEIA [2, 4].
- Reduction of operation costs: DAS will significantly reduce outage time, unnecessary switching operation and maintenance costs, as well as non-delivered energy and penalties eventually paid by utilities to customers. Direct costs for management of incidents in power network will reduce 0.4% EEIA [2, 4], whereas reduced penalties, if paid to customers, can reach the value up to 4% EEIA [2, 4].
- Reduction of network construction costs: ADMS functions for power restoration, network reinforcement, analysis of new connections and long-term planning can improve utilization of facilities and postponement of investments, providing benefits 0,5-1% EEIA [2, 4].

The total benefits of DAS may be reached annually:

- Minimum 2% of EEIA market value, if no compensation (penalties) is paid by utility,
- Maximum 6% of EEIA purchase value, if compensation (penalties) is paid by utility for outages.

The AMI benefits

Application of AMI system can bring benefits in several areas.

- Automated meter reading, data processing and billing of customers will reduce meter reading costs, improve accuracy of consumption data, as well as improve remuneration of electricity bills. Traditional meter readings were manual, with high labor and field costs, low accuracy and not synchronized with purchase side. Automated meter reading will avoid labor and field costs (approx. 2% EEIA , assuming approx. 1 Eur/meter reading costs in 4 times per year), whereas higher accuracy and billing of customers will improve financial income with benefits in range 1-2% EEIA [2].
- AMI consumption data, now accurate and synchronized with power measurements and power flow calculations, integrated with DMS Energy Audit functionality, will accelerate theft detection, providing benefits in range 1-2% EEIA [2].
- The AMI infrastructure will be used by outage management system to get status and measurements on customer side in real-time, or to receive *trouble calls* in case of inci-

dents, significantly improving outage management process in Low Voltage networks and reducing outage time. Similarly to DAS fault management improvements, benefits will be in range from 0.5% EEIA for direct utility costs, up to 4% EEIA if penalties are paid by utility to customers.
- The AMI infrastructure will support efficient communication between Demand Response Control system and controlled devices, reducing investments in DRS communication system.

The total benefits of AMI may reach annually:
- Minimum 5% EEIA market value, if no compensation (penalties) is paid by utility,
- Maximum 10% EEIA market value, if compensation (penalties) is paid by utility for outages.

The DRS benefits

Demand response is used primarily to reduce the peak load of the power system or on the local level, with a goal to avoid emergency situation because of non-sufficient power capacity in the production or network side. In this analysis, DRS will be considered as *utility tool* for peak load management, bringing the following benefits.
- Peak load reduction on the network level, leading directly to reduction of power and energy costs in peak hours, which are lasting 2-3 hours per day. DRS can reduce 5-10% of the peak power, depending on technology applied and the number of participants. Since the price of the power/energy in peak hours is 5-10 times higher than the price in off-peak times, benefit using DRS equals approx. 5-10% of EEIA market value.
- Increased network reliability – network is not loaded up to maximum and there is available capacity without exceeding operational margin. In case of large dis-balances of power or energy, DRS will reduce black-outs, providing benefits in range of 2% EEIA.
- The DRS will provide better utilization of network facilities, postponing expensive investments in network construction, providing benefits in range of 1% EEIA.

The total benefits of DRS may reach 8-10 % of EEIA market value annually.

DER management benefits

Smart management of DER capacities may bring reduction of power losses in distribution network, reduction of overloads on the local level, and improve power quality. DERM application performs optimal scheduling of resources, short-term planning and balances of the energy flow, control of voltages and power quality. The first implementations have just started, and first experiences are proving possibilities to achieve benefits [12].

Investments in smart grid solutions

The SGS investments encompass field equipment, communication systems, computer hardware, software, implementation services, trainings and support. Investments in all groups of SGS concept are analyzed in this chapter.

The DAS investments encompass the following sectors.
- The ADMS software and hardware, deployed in data server centers (main and back-up) and control centers (users workstations), including data engineering, customization, delivery, training and testing of the system.
- Remote terminal units (RTU) or substation automation systems, implemented in high voltage substations and on many locations in medium voltage network (service substations or pole mounted switches), including equipment for signal conversion (transducers, relays),

ancillary equipment and services (power supply, assembling), testing and commissioning of the system.
- Communication systems (radio, fiber-optic, mobile providers), including system design, licenses, deliver, training, testing and commissioning of the system.
- Power equipment capable for remote control actions (ring main units in service substations, motorized power switches on poles, voltage regulators, *etc.*)
- Distribution network has to be automated up to the certain level, to be capable for efficient remote control and execution of ADMS optimization steps in a real time or closed loop, which implies automation of all substations and certain number of critical distribution points (3-4 automated points per distribution feeder). Considering all necessary investments, using several examples and real cases, the DAS investment costs can be estimated on 12% of EEIA market value [2, 4].

The AMI investments include:
- Smart meters with communication modules, including delivery, installation and testing on customer connections sites,
- The AMI communication system, including system design, licenses, delivery and installation of communication equipment, testing and commissioning of the system,
- Network management software, implemented in data server centers, including software and hardware, delivery and testing.

Typical AMI investments are in range of 100-120 Eur/meter or approximately 40% of EEIA.

The DRS investments include:
- The DRS Management Software, implemented in Data Server Centers, including Software and Hardware, delivery and testing,
- The DRS communication system, including system design, licenses, delivery and installation of communication equipment, testing and commissioning of the system. Nowadays, AMI infrastructure is often used as communication system between DRS center and end consumers in case of *direct load control*. Recently, web-portal and internet is used for exchange of information.
- The DRS local devices on consumer side, different kind of signal receivers and meters, control switches, home automation technology, AMI meters, *etc*.

The DRS investments with direct load control applied in wide areas are in range of 20% of EEIA.

Cost benefit analysis

The cost/benefit analysis considers all costs and benefits in the life time of SGS systems. Analysis is applied on example of a large utility supplying 1,000,000 meters, with1500 MW peak load, 5000 hours duration, having EEIA of 7500 GWh/year. The market value of EEIA is approximately 225 Million Euro (MEur), using average market wholesale price of 30 Eur/MWh.

Estimation of costs

The first step of cost/benefit analysis is to estimate the full cost of using SGS system:

Considering all SGS solution, the total initial investment costs (I_0) would be approx. 72% of EEIA, as analyzed in Investments in smart grid solutions, or 162 MEur in example of a large utility. Apart from initial investment cost, SGS would have certain *annual cost* during the operation during the life time (T). The life time of SGS solutions is typically 10 years (combination of computer, telecommunication, automation, and electronic equipment). SGS annual cost can be presented:

$$C_i = (d\% + m\% + int\,\%)I_0\,,\, i = 1,...T\,, \tag{1}$$

d% – average depretiation of SGS system (1/*T*), it is 10% in case of 10 years lifetime,
m% - maintenance and operation cost – typically 2%,
int% - interest rate, typically 6%.

The SGS system annual costs would be 18% of initial investment costs, or approx. 29 MEur/year.

The total cost of ownership (TCO) is considering the total cost over the lifetime of the system, using weighted average cost of capital (wacc%) as a discounting factor:

$$\text{TCO} = \sum_{i=1}^{T} \frac{(d\% + m\% + int\,\%)I_0}{(1 + wacc\%)^i} \tag{2}$$

If the amount of annual depretiation, maintenance cost and interest cost is constant over time, the eq. (2) can be expressed with discounting total factor (DTF):

$$\text{TCO} = (d\% + m\% + int\,\%)I_0 \cdot \sum_{i=1}^{T} \frac{1}{(1 + wacc\%)^i} = (d\% + m\% + int\,\%)I_0 \cdot \text{DTF} \tag{3}$$

Using the current wacc% value of 6%, DTF has the value of 7.36, and we can calculate TCO:

$$\text{TCO} = 18\% \cdot I_0 \cdot DTF = 18\% \cdot I_o 7.36 = 1.3248 \cdot I_0 \tag{4}$$

In the example of a large utility, with Io of 162 MEur, the TCO would be 215 MEur.

Estimation of benefits

The second step in cost/benefit analysis is to estinmate the full benefit of using SGS.

The annual benefit of using SGS systems, as discussed in the section *Smart grid benefits*, will include benefits of applying DAS systems, AMI, DRS, and/or DERM systems. In case the utility is not paying any compensations or penalties due to incidents and outages in the power grid, which is very unlikely, the annual benefit would be approx. 15% of EEIA. However, due to regulation policy, utilities are obligated to compensate certain amount of damages to consumers in case of outages, or they are exposed to penalties, when benefits are higher and may go up to 25% of EEIA. The SGS benefits sensitivity on the level of compensation paid to customers will be considered. The annual benefit can be presented by:

$$B_i = (15\% - 25\%) \cdot \text{EEIA}_i\,,\, i = 1,...T \tag{5}$$

In the example of a large utility, with EEIA of 225 MEur, the annual benefit will be in the range 34-56 MEur. In the life time of the system, benefits will be discounted with the same discounting factor (wacc%), giving the total benefit of ownership (TBO):

$$\text{TBO} = \sum_{i=1}^{T} \frac{(15\% - 25\%) \cdot \text{EEIA}_i}{(1 + wacc\%)^i} \tag{6}$$

In case EEIA is the same every year, the eq. (6) can be simplified using the discounting total factor (DTF):

$$\text{TBO} = (15\% - 25\%) \cdot \text{EEIA} \sum_{i=1}^{T} \frac{1}{(1 + wacc\%)^i} = (15\% - 25\%) \cdot \text{EEIA} \cdot \text{DTF} \tag{7}$$

In the exampe of a large utility with EEIA of 225 MEur, we can calculate TBO:

$$\text{TBO} = (15\% - 25\%) \cdot \text{EEIA} \cdot 7.36 = (1.1 - 1.84) \cdot \text{EEIA} = (1.1 - 1.84) \cdot 225 \text{ MEur} = 248 - 414 \text{ MEur}$$

Cost-benefit analysis

The four economic factors are considered in the cost/benefit analysis:

$$P = \frac{\text{TBO}}{\text{TCO}} \tag{8}$$

Profitability (P), as ratio between total benefits and costs during the lifetime of the system, if $P > 1$, the project is profitable.

$$Payback = \frac{T}{P} \tag{9}$$

Payback – Payback period, or the period of time necessary for return of investment. If the project is profitable then payback period will be less than the lifetime, and project will produce profit.

$$\text{ROI} = \frac{\text{TBO} - \text{TCO}}{\text{TCO}} \tag{10}$$

Return on investments (ROI), the factor showing added benefit after the return of investment during the lifetime of the system.

$$0 = -I_0 + \sum_{i=1}^{T} \frac{B_i - C_i}{(1 + \text{IRR})^i} \tag{11}$$

Internal rate of return (IRR), the discounting factor which would discount annual profits on the amount equal initial investment. The IRR is showing if and how much the investment is profitable, comparing with the average rate of the capital.

Since benefits may have different amounts, as presented in eqs. (5) and (7), which has significant impact on all four economic factors, sensitivity analysis was made in this benefit range. The benefit was varied in the range between 15% and 25% in steps of 2.5%: If utility is not paying any compensation (penalties) for power outages, the annual benefit is 15% EEIA; if paying 25%, the benefit is 17.5%; if paying 50%, the benefit is 20%; if paying 75%, the benefit is 22.5% and if paying 100% or the full compensation (penalties) for power outages, the annual benefit is 25% of EEIA. The results of sensitivity analysis are presented in tab. 1 and figs. 2-5.

Table 1. Cost – benefit sensitivity analysis for different penalties rates

TCO	TBO	Penalty rate	P	ROI	IRR	Payback
214,620,138 €	248,402,938 €	0%	1.157	16%	14%	8.6
	289,803,428 €	25%	1.350	35%	18%	7.4
	331,203,917 €	50%	1.543	54%	22%	6.5
	372,604,407 €	75%	1.736	74%	26%	5.8
	414,004,897 €	100%	1.929	93%	30%	5.2

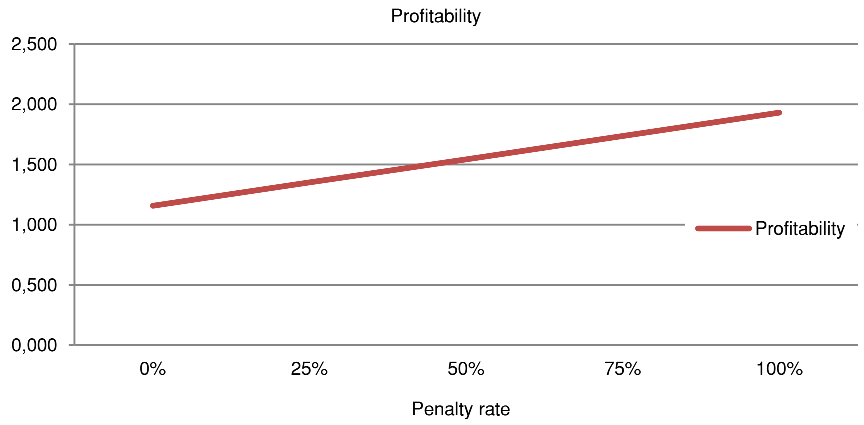

Figure 2. Profitability of SGS projects with different penalties rates.

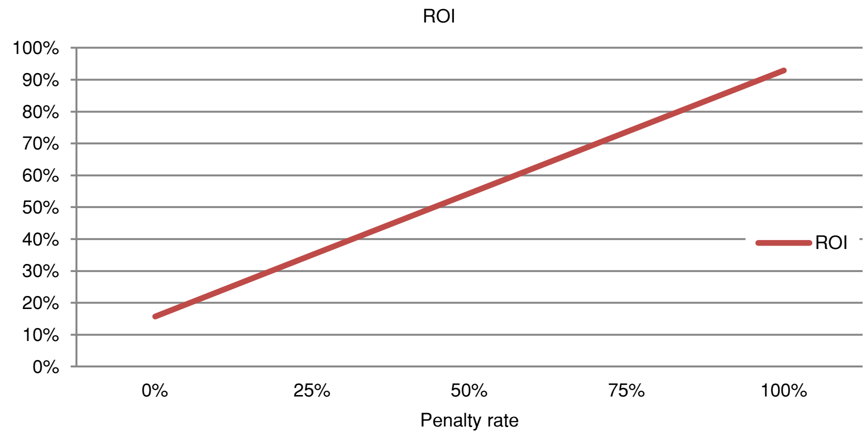

Figure 3. Return on investments for SGS projects with different penalties rates.

Figure 4. Internal rate of return for SGS projects with different penalties rates.

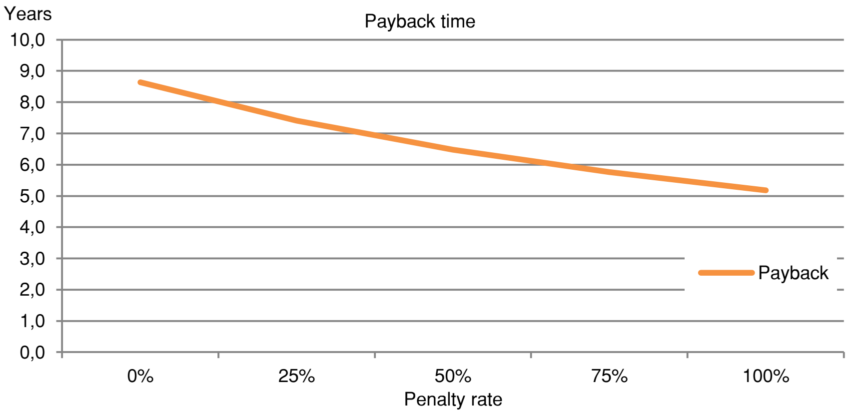

Figure 5. Payback time for SGS projects with different penalties rates.

Cost-benefit analysis results are showing that SGS projects are always profitable, whereas profitability depends on the level of compensation to customers for outages, or penalties to which utilities are exposed.

Conclusions

Smart grid solutions can significantly improve power network operation, increase reliability, safety and quality of supply. Regarding quantification of SGS benefits and comparison with related costs, the biggest challenge facing utilities today is to estimate real profitability of such investments.

According to cost/benefit analysis presented in this article, it can be concluded that SGS projects are profitable investments. Profitability depends on the level of compensation paid by utility to customers for outages in power network operation, or on the level of regulatory penalties to which utility is exposed. Considering ten years lifetime of operation, the following conclusions can be made for a large utility.

- If utility is not paying any compensation (penalties) for outages, which is unlikely, SGS projects will still be profitable, with lower profitability of 1.1, payback period of eight years, 16% ROI and 14% IRR, which still may be attractive for investors.
- If utility is paying certain compensation (penalties) for outages, SGS projects will be more profitable, with profitability up to 1.9, payback period down to five years, ROI up to 93% and IRR up to 30%, which makes SGS projects very attractive to investors.

Taking into account that this cost/benefit analysis is considering only SGS benefits which can be financially evaluated, but not all possible benefits which cannot be precisely calculated (*e.g.* customer satisfaction, reducing CO_2 pollution, safety on work, *etc.*), SGS profitability is even better then calculated.

In general, taking into account all benefits, it can be concluded that SGS are very profitable investments, with almost double profitability and quick return of investments in five years. In short, on every invested Euro, double will be returned during the lifetime of the system.

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