Towards Smart Street LED Lighting Systems and Preliminary Energy Saving Results

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***Abstract* – The article gives an overview of various researches dealing with smart or intelligent street lighting systems, and what is meant with this term in different countries. Several available architectures of smart street lighting systems as well as those for future are described and discussed. Further some researches and developments of such systems in Riga Technical University are explained with the examples, also showing preliminary practical energy saving results of tests in real conditions of Riga city infrastructure. This is the first part of articles series about this research.**

***Keywords* – LED lamps, lighting, lighting control, smart grids.**

I. Introduction

The street lighting system is a necessity in order to have safe city traffic and increase comfort level for citizens, and in most cases the lighting systems tend to be as wide as the city street layout itself, therefore it has a lot of luminaries, consuming a significant amount of electrical energy.

During the past several years, a new lighting street technology, basing on Light Emitting Diodes (LED), has come into the market. First LED street luminaries were quite simple, and were mainly supposed to replace High Pressure Mercury vapour light source based luminaries. At the beginning luminary price was high, for example, in Riga (Latvia) at year 2009 165W JOLIET 6 High power LED streetlight luminary costs were around 1200EUR, with efficacy only 64 Lm/W [1]. Nowadays the efficacy of LED luminaries (for example Philips, Thorn, Schreder, Cree) has been about twice increased, at the same time decreasing the price of it for almost 50 %, thus enabling compete with High Pressure Sodium vapour source based luminaries, in terms of energy efficiency. These technological achievements also allow a continuous increasing LED indoor and street luminary market share in the global lighting market, which is also reflected in various high-brightness LED market forecasts.

The current lighting networks and systems, that are designed for High Pressure Sodium (HPS) vapour source luminaries, typically have centralized control systems, mainly used only for powering ON or OFF the electrical cabinets (or substations) where several sub-cabinets and streets with luminaries are connected. In this case the lighting network control signal is transferred by means of Radio or GPRS communication method. The system has a calendar graphic/table, where ON/OFF time is specified for each day, during the whole year, then the control command can be sent automatically or by system operator (personnel). For smaller cities and areas, in order to obtain more savings, it is common to use also delay timers, especially for low traffic streets, in this case light comes ON later, than in the rest of city, at the same time also that smoothes out the load pikes on the electrical grid. In some countries [2] a popular solution for automation is to install twilight switches (Integral photoelectric sensor like “Finder 10.51”) in electric cabinet, or even use embedded brightness sensors for each luminary, especially common in autonomous LED based luminaries [3–5], powered from accumulators charged by solar panels, or in combination with wind turbines or AC grid [6]. Of course some city HPS based lighting systems (or electric cabinets) are controlled by systems like Reverberi Enetec [19], by means of stabilizing AC line voltage and for HPS dimming – decreasing the voltage level, thus decreasing the lamp power and light output. The communication can be made via Power-line Carrier, full management GPRS modem, as well as GSM and Ethernet interface, thus enabling power metering for whole line. It can be said that such systems are first smart (smarter) systems compared to described previously, enabling energy savings already for HPS systems in a range from 25 %–40 %. The disadvantage is that HPS lamps could be regulated just from 50 % to 100 % and can cause color shift and color rendering index (CRI), as well as significant drop of luminous efficacy (lm/W), also it takes a time for lamp to heat up, in order to get max luminous output.

When the time passes all control systems become more and more advanced (smarter), thus it happened in street lighting control systems. If the first LED luminary ballasts were without LED driver – a special circuit for constant current regulation, then few years later most of the LED luminary manufacturers equipped ballasts with the constant current drivers, power factor correction (PFC) circuits, and lately also with dimming inputs, thus enabling to utilize LED main advantage – to instantly regulate light output in full range - from ~0 % to 100 % with no photometric parameter changes. This is also main feature that is important driving force for the research and development of more advanced lighting control systems in past few years, both for universities and industry. Lots of new LED luminaries and lighting control system examples can be seen in exhibitions like Light&Building.

Further article describes research and practical results obtained at Riga Technical University projects related to street lighting system development and such system testing in real life conditions.

II. Smart Street Lighting Systems

A. Definition

There are numbers of research articles available that are mentioning term "smart street lighting system" or "intelligent street lighting system". And here the question arises, what exactly smart street lighting system is, and where it came from. Also within these numbers of articles like [10–14], who have in titles these terms like "smart" or "intelligent" lighting system, in the text actually does not reflect the meaning or explanation – why it is "smart" or "intelligent", only few of them [2,6] give or use reference that explains what the authors meant with this terminology. At first it seems, that most people just grabbed fancy word and added to the article title, just to make it sound more important.

Thus another question arises again when and what we can call "smart" or "intelligent" street lighting system. When looking for definitions for these terms in IEEE standards and definitions, there is no explanation yet, but you can find only separate or similar words, like "Smart Grids", "intelligent electronic device (IED)" [7], that says it is "any device incorporating one or more processors with the capability to receive or send data/control from or to an external source", and "smart transducer", that "provides functions beyond those necessary for generating a correct representation of a sensed or controlled quantity, simplifying the integration of the transducer into applications in a networked environment". Thus it could be agreed that "smart" means ability to be a part of network – send/receive data, and have parameters above common system with an added value or special functions.

Also "street lighting system" is a part of electrical "grid" and also "city", therefore when term "Smart Grid" was introduced, "smart lighting systems" and "Smart City" became more and more common in literature. It could be said, that in future smart street lighting network will be a part of smart city, like city of Quebec added a bus lane control system to Echelon's Street Lighting Solution and eliminated the cost of a second infrastructure [8]. Also the smart lighting grid can be used for harvesting energy from micro-generators, like wind turbines, solar panels, etc.

B. System Architectures

Some cities (for example Riga city) still use lighting system with control method as described in [9], where Main Control System (MCS) is controlling one electric cabinet equipped with Automated Control System (ACS) and current measurement devices, which then can give feedback signal, back to MCS through radio frequency communication signal (other cases use GSM or GPRS signal).

Also during the last couple of years, Riga city, like many other cities across the world, started to install first LED luminaries, at the same time not changing the existing network or control system layout. In this case Fig. 1 shows the LED luminary layout and connection to existing AC lighting network. These LED luminary drivers did not have inputs for dimming signals, in order to increase or decrease the power and thus light output.

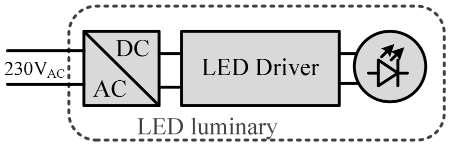

Fig. 1. LED luminary layout and connection to existing lighting network.

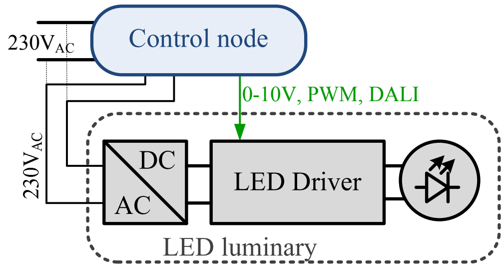

Fig. 2. Architecture with control node.

As the energy savings for LED system that only replaces the mercury or sodium (HPS) vapour lamps were not high enough in terms of investment payback time (also return of investment (ROI)), new LED luminaries as shown in Fig. 2 were developed and proposed to market. In this case system replaced the ballast that now has dimming inputs (typically 0–10 Vdc, PWM, DALI- digitally addressable lighting interface), in order to change the LED PCB plate driving current, thus it's possible to regulate the consumed power. Also such system needed a control node, for example "Philips DynaDim", "Vossloh Schwabe iMCU", "Schreder LuCo-AD", etc.), that controlled LED driver, according to preprogrammed power levels for each day, according to calendar graph. Such system is good for smaller cities with smaller budget, as it is saving energy during the night time, but the problem is that programming is done in the factory, and typically it is quite hard to reprogram it if necessary, also the LED luminaries were not connected to central management system, thus it is not possible to see the power status or failures.

Therefore new control nodes, as shown in Fig. 3, were developed, that have communication circuits and thus ability to send/receive data from central management system through a gateway. Such architecture can be called as smart street lighting system, as it is described in various researches like [9–14].

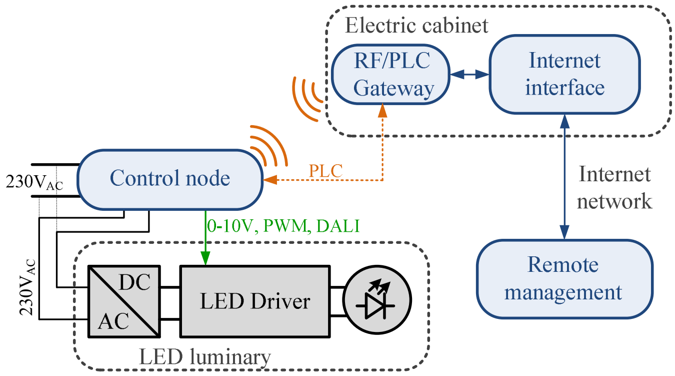

Fig. 3. Architecture with control node with communication circuit.

As it can be seen from Fig. 3 control node communication can be realized via Power Line Communication (PLC) or wireless/radio communication, like ZigBee. In this case control node is a separate device that can be installed in the luminary, or in the lighting pole. Further the gateway sends/receives data from control nodes and transfers them to the internet. The luminary power levels are predefined for the each hour of the night-time, thus there are some minimum or maximum light output levels, and energy savings are based on those settings.

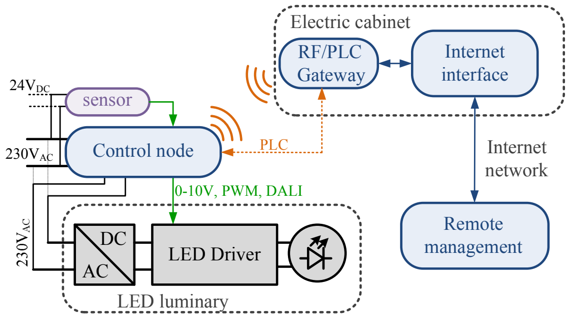

Fig. 4. Architecture with control node and movement detection sensor.

To make the system smarter or give it ability to work in decentralized way, a movement detection sensor must be added to the system, as shown in Fig. 4. The sensor can be powered from AC mains (230 V), or with separate power supply – 24 V DC (typically). In this case the command to increase or decrease light output level (also power) can be given by this sensor, where the triggered luminary via control node can send “ON” signal to the closest luminaries, thus lighting up the lamps in advance of traffic participant.

In case of system shown in Fig. 3, the minimum light output level must reach at least the lowest road lighting class values described in EN 13201 standard, for example ME6, thus there are limits regarding the minimum light output level (typically 30%–50% of nominal power) and possible energy savings. In case of the system shown in Fig. 4, the sensor brings luminary at full or maximum preprogrammed power only when it is needed, respectively – when presence of car or pedestrian is detected. Thus it is possible to maintain even more lower level of the luminary light output, for example 10%–15%, in this way getting even more energy savings.

To make system more robust and thus more attractive to lighting market, it is wise to make the LED power supply with integrated control node, as shown in Fig. 5.

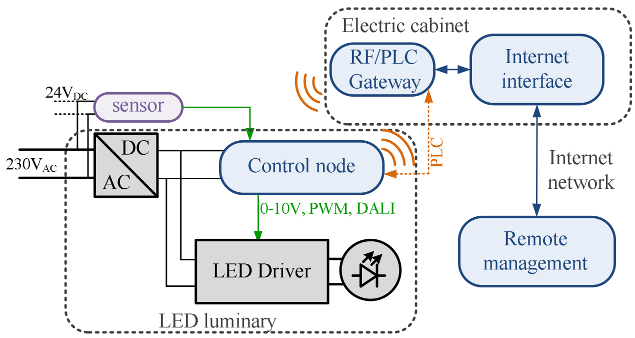

Fig. 5. Architecture with embedded control node and movement detection sensor.

Typically lighting grid network is switched OFF during the daytime, in order to avoid conductive losses in the power lines, thus the luminaries also are offline. The city lighting grid is large, and it is possible to apply Smart-Grid or Smart-City concept, if we would add the wind generators or solar panel arrays to the existing AC powered system, like it is shown in Fig. 6. The mentioned alternative energy sources can be also microgenerators, placed on the top of the lighting poles, for example research done in [6]. Anyway special power converters, will be needed for this system, and various new topologies, like [15,18] are available.

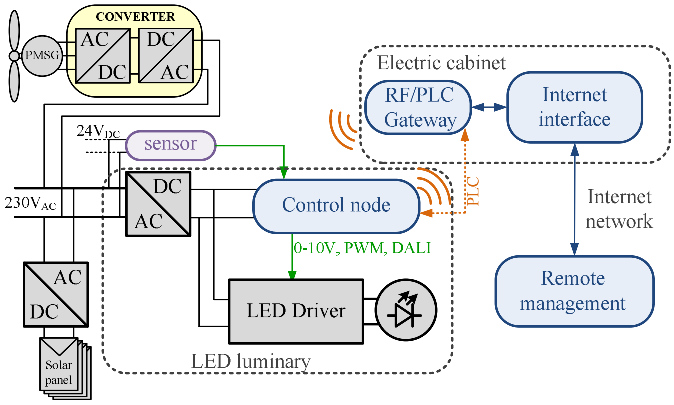

Fig. 6. Architecture with AC grid connected renewables.

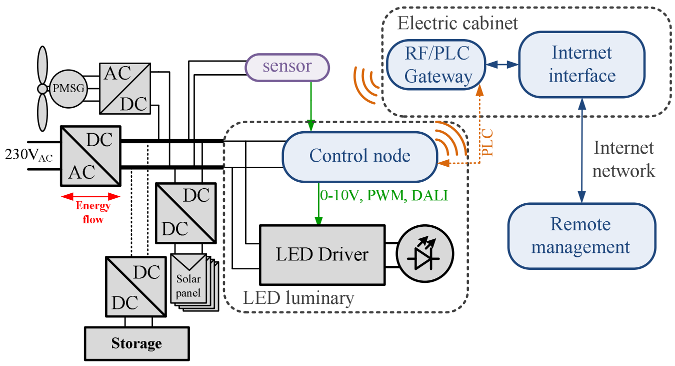

Fig. 7. Architecture with DC grid connected renewables.

The next step could be implementation of DC-Link in the lighting system power grid, this approach would decrease losses in AC-DC converters used to power LED luminaries and also for solar/wind energy injection in the Grid. In this way only DC-DC converters are needed, which have efficiency above 92 %, typically close to 98 %, and there are no Electromagnetic Compatibility issues or problems related to cos(f) or THD. Also different modulation techniques [16] can influence the total efficiency of the LED driver, as well as the power supply methods for intelligent LED luminary [17] If we add energy storage element (capacitor, Lithium-Ion, etc.), it can even shave the power peaks, which happen when all luminaries are switched ON at first time of the evening. This approach should be investigated more deeply, focusing on conductivity losses in the power lines and create a power supply that is able to switch off output, while input could be powered by renewable energy sources.

III. Analytical Architecture Comparison

Municipality (or other end-user), could use one of architecture described in Fig. 1–Fig. 7 for the street lighting system, but it is not obvious what is best solution in terms of energy savings and ROI (Return Of Investment). Further we will analyze architectures shown in Fig. 1–Fig. 5, where analysis is based on research data obtained within EU project LITES [22] and various street lighting retrofit projects in Latvian municipalities, mainly dealing with retrofitting high pressure mercury vapour and sodium vapour based luminaries to LED based luminaries.

A. Common Evaluation Parameters

In order to compare different architectures, we need to set-up common basic starting conditions. As High Pressure Sodium (HPS) luminaries are quite common in European street lighting systems, as first condition for calculations we assume that existing street consists of 30 pcs of HPS luminaries, in this case we select Philips Malaga SGS102 150 W (12425Lm) with HPS lamp SON-TPP150W (total cost 150 EUR/pc). As equivalent to HPS we select LED luminary manufactured by Philips Indal BGP623 with 8300 Lm and power 71 W (approx. 430 EUR). The selection is based on Dialux calculations for real ME4-ME6 class street profiles and complies with according normative parameters, but in other situations there can be differences. Thus the total installed power of HPS lighting system is 5,07 kW and for LED system – 2,667 kW.

Further it is necessary to determine common lighting system ON/OFF timing, thus Fig. 8 shows sunrise and sunset timing for each month of the year, in order to get maximum possible working hours of the system we exclude twilight times. In this case we get 4352 lighting system working hours per year, which is used in further calculations.

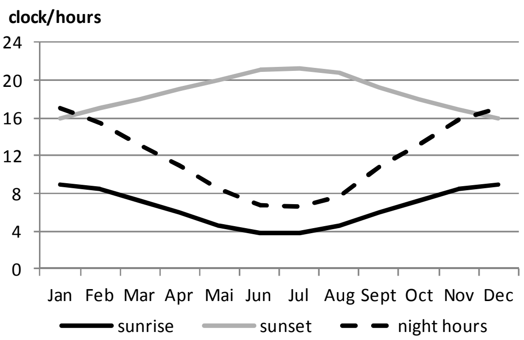

Fig. 8. Monthly time of sunrise/sunset hours per year.

As the architectures shown in Fig. 2–Fig. 5 are exploiting dimming (light output regulation) capabilities, it is necessary to set-up also common dimming profiles, defining the number and length of the time on the zones during the night, as it is shown in Fig. 9 and Fig. 10 is based example available in [21].

Further selection of dimmable LED luminary light output values is partly based on [21,22] as well as materials from Latvian municipality most common choices in retrofit projects. For calculations minimal light output values for dimming profiles shown in Fig. 10 are used.

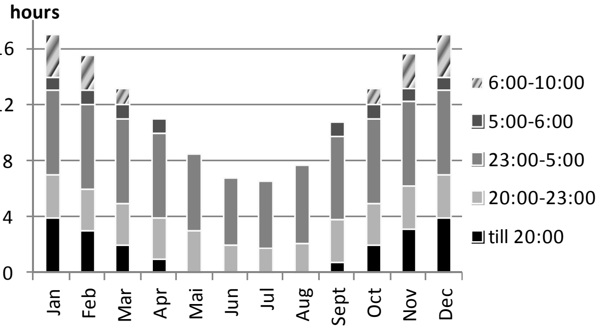

Fig. 9. Monthly night-hours for dimming profiles.

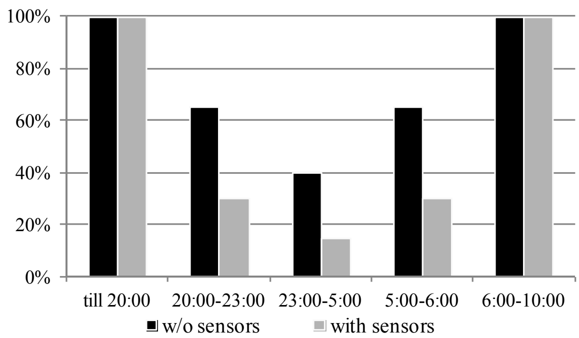

Fig. 10. Minimal light output values for dimming profiles.

From parameters shown in Fig. 9 and Fig. 10 we can calculate average light output values per year, where for lighting systems without sensors (Fig. 2 and Fig. 3 architecture) it is 61 %, but for systems (Fig. 4 and Fig. 5) with movement detection sensors it is 39 %, as we can use lower minimal light output values.

Further we need to take into account also consumption from peripheral devices, like control nodes (controller and communication device), sensors and gateway devices (Fig. 2–Fig. 5). For the system shown in Fig. 2 we can use Philips Dynadimmer controller (without communication function), and in this case we need 30 such devices, where each has 0.5 W consumed power [21], device costs approx. 30 EUR/pc.

For control nodes with ZigBee, like [23] with average cost of 50 EUR, or Power Line Carrier (PLC), like [24] with average cost also 50 EUR, communications we assume that in average stand-by plus transceiving regimes these devices has maximum 3 W consumed power. In case of communication ZigBee or PLC gateways, for example Teliko C-Box [24] with price 460 EUR, that enable data transfer to the internet (Web server), stand-by consumption is 15 VA, but transceiving regime it is 20 VA, so we can assume that average consumption is 17,5 W.

For systems shown in Fig. 4 and Fig. 5 we use movement detection sensors, like Steinel IS3180 [25], with 0,9 W consumption power and price of 80EUR. Such sensors must be placed on each lighting pole, as their range is only 20 m at 2 m height. For electricity cost calculations a fixed average price - 0,125442 EUR/kWh is used, as in Latvia, for lighting systems special rate “T-9” is used, with different price ratio for night (and weekend) hours and day-time hours.

B. Analytical Results

From calculations, the yearly consumption for LED luminaries (excluding peripheral devices) is 11654 kWh/year (installed power is 2,677 kW).

Typically it is considered that peripherals, like controllers, communication nodes, sensors, etc, are consumers below 1 W, and typically are negligible, but in reality they can consume up-to 5 %, as shown in Table I. In case of Fig. 4 and Fig. 5 the difference is because the control node is embedded in power supply, therefore less losses in converters.

TABLE I
PERIPHERAL CONSUMPTION INFLUENCE ON TOTAL CONSUMPTION

Architecture	Peripherals		% from total consumption	Total investment
	P, W	*E*, kWh/year	%	EUR
Fig. 1	0	0	0,0%	12900
Fig. 2	15	65,29	0,6%	13800
Fig. 3	107,5	467,88	4,0%	14860
Fig. 4	134,5	585,40	5,0%	16360
Fig. 5	74,5	324,25	2,8%	16360

Further Fig. 11 shows potential (as obtained analytically) energy savings for architectures (Fig. 1–Fig. 5.), compared to existing HPS based lighting system. As it can be seen, with simple retrofitting (Fig. 1.) it is possible to get energy savings up to 47 %, but adding more controls and functionality ("smartening the system"), it is possible to get additional 20 %–30 % energy savings.

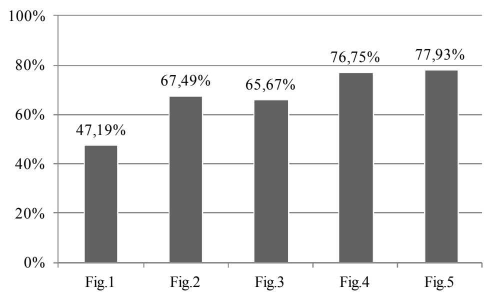

Fig. 11. Potential energy savings compared to HPS system.

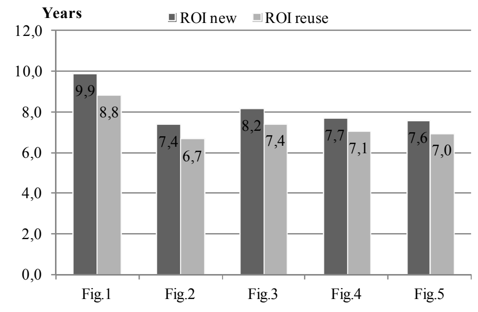

Fig. 12. Return of investment values.

If looking from return of investment (ROI) point of view, the system payback time is shown in Fig. 12, where only profit from energy savings are taken into account (no costs of HPS lamp replacement during maintenance period added). Fig. 12. also shows two ROI values, where darker one is for new and retrofitted systems, and the other is when the old HPS systems are reused for spare parts.

IV. PILOT SITES AND PRELIMINARY RESULTS

During research and development projects Riga Technical University has created three pilot sites in Riga city to test smart street lighting systems with LED luminaries.

Pilot Site at Mezha street is using architecture shown in Fig. 2, system replaced 18 pcs of 85–120 W HPS luminaries to 60W LED luminaries, where communication and control is done only via ZigBee network, implementing calendar graph ON/OFF timings, this gave 40 % energy savings, using "dimming" function was added during night – savings were 51–72% (average per year was around 60 %). Larger savings are due to existing luminaries were oversized in terms of light output.

PilotSite in Rietumu street is based on Fig. 3 architecture, replacing 22 pcs 114–120 W HPS luminaries with 22 pcs 74 W LED luminaries, where ZigBee is initial communication network, but GPRS is used to transfer data to database. This gave 37 % energy savings from retrofit only, but using dimming function – it increased to 49 %–83 % (average per year – 59 %). Large savings were obtained due to fact that luminaries were oversized, thus also large light pollution was in that area. With special secondary optics (lenses) it was possible to obtain even better light uniformity, thus less power was needed.

Further experience from LITES project [22] will be discussed, where smart LED lighting system (Fig. 4) is tested in real life conditions in three European climate zones, where first PilotSite is in Bordeaux, second is in Aveiro and the third is in Riga. Riga PilotSite is located in Zunda krastmala, system consists of 29 luminaries, where 12 are 95 W and 17 are 65 W luminaries. Preliminary results show that from installation date (February 2014), energy savings are 70.8 %, and it increases, as the nights become longer. The movement detection sensors installed on the poles, allowed decreasing the minimum light output level to 15 %.

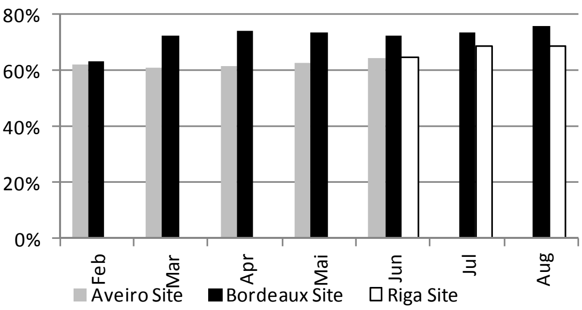

Fig. 13. Energy savings in LITES project Pilot Sites.

Fig. 13 shows the energy savings for all LITES project pilot sites, and it can be seen that the values are less, but still close to the potential energy saving calculations shown in Fig. 11. Furthermore, in Riga PilotSite a special energy counter is installed into the lighting poles, to compare the readings from nodes. Initial measurements show that difference is 1,4 % in average (nodes show more consumption). Therfore actual savings in Riga PilotSite for June is 66 %, for July is 70,80 % and for August – 71 %.

V. Conclusions

From architecture analysis, it can be seen that smart street LED lighting systems (Fig. 4, Fig. 5), even with higher investment costs (see Table I), have the highest energy savings and fastest ROI time.

The numbers in terms of energy savings using smart street lighting systems are similar for various researches [2]–[6], and the Pilot Sites in Riga justifies that with practical measurements.

The next task is to analyze for obtaining comparable energy saving and ROI values for architectures shown in Fig. 6–Fig. 7. Further it is planned to continue monitoring LITES system and test smart street lighting system based on Zigbee-WiFi communication [9], installing 8 luminaries in campus location.

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