E+GRID: Energy-positive adaptive street lighting

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ABSTRACT

This paper introduces the energy-positive adaptive street lighting *(E+grid)* concept, a novel outdoor lighting system comprising state-of-the-art adaptive LED luminaries equipped with motion sensors, integrated with photovoltaic (PV) energy generation, battery storage, bi-directional grid connection, and a cloud-deployed central controller with a web-based user interface. *E+grid* is designed to be self-sustaining: the energy generated by the PV panels exceeds the energy consumption of the luminaries on a one-year horizon. The paper reviews the key system components and reports on simulation experiments to calculate the yearly energy and financial balance in the system.

INTRODUCTION

Energy-positive street lighting (*E+grid*) is a novel outdoor lighting concept developed by GE Lighting and three Hungarian academic research institutions. The core components of the system are the intelligent dimmable luminaries which adapt automatically to the actual environmental and traffic conditions, using motion sensors mounted into the lighting fixtures. Street lighting is integrated with solar energy generation and battery storage, and the system is connected to the smart grid. The performance of the units is monitored by smart meters that provide feedback for remote control decisions. The signals of the twilight switch in the local weather station are used to determine the daily switch on and switch off times of the luminaries. The weather station also measures six further weather parameters, which serve as input to the short-term prediction of the PV energy production and the performance evaluation of the energy management system. All system components transmit data to a central computer, providing information on the status of the light points, the energy flow in the system, traffic intensity, and maintenance needs via a web-based graphical user interface. The architecture of the system is depicted in Figure 1.

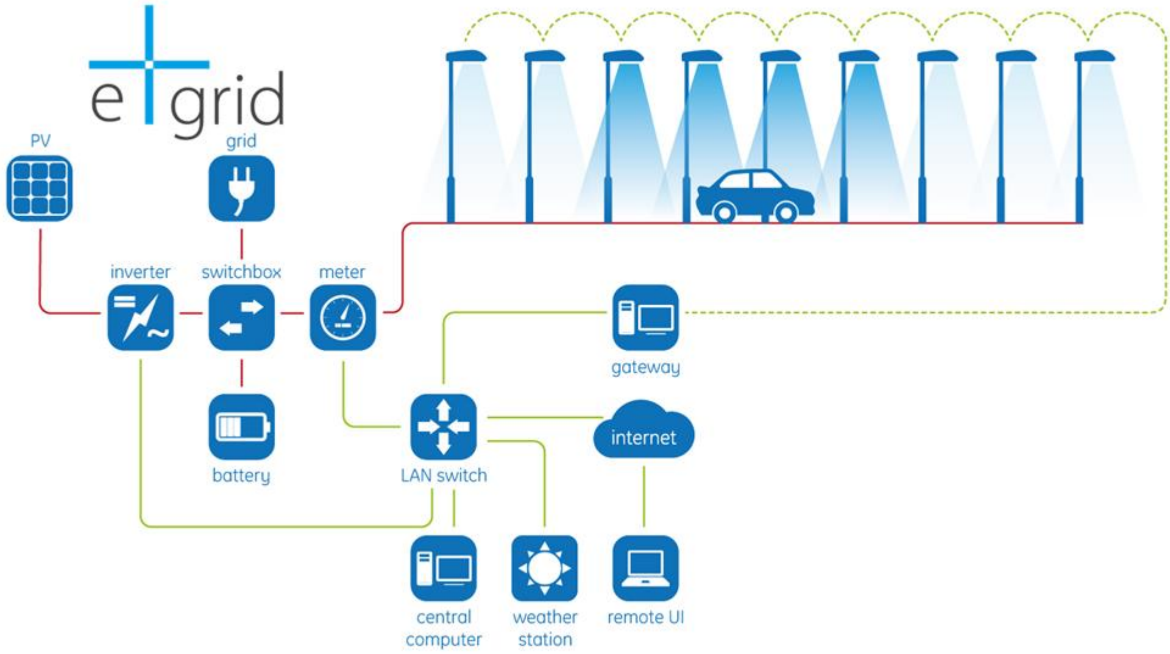

Figure 1. Architecture of the E+grid system.

E+grid is designed to be self-sustaining at the geographical location of the installation: the energy generated by solar panels exceeds the energy consumption of lighting on a yearly horizon. Seamless connection of the ICT-based system to the smart grid will enable communities to become a player in energy market. *E+grid* delivers cost savings and extra revenue in several ways: by powering street lighting with solar energy stored in batteries, by feeding solar energy into the electricity grid, and by trading with electricity via exploiting variable energy tariffs. *E+grid* also contributes to the significant reduction of CO_2 emission, and to stabilizing the electrical grid. Below, the key components of the *E+grid* system are reviewed.

ADAPTIVE LIGHTING SYSTEM

The *E+grid* system achieves adaptive, energy-efficient lighting by adopting state-of-the-art, dimmable LED luminaries, which adjust their lighting intensity with respect current traffic and environmental conditions. Infrared motion sensors, mounted into the lighting fixtures on each pole, measure the speed and the direction of the motion. Smart controllers, in turn, classify these motion signals as vehicle traffic, pedestrian traffic, or no traffic, and adjust their dimming levels to the detected scenario. However, luminaries are not isolated; they inform their neighbours about the detected traffic scenario via wireless communication, enabling the long-range adaptation of the lighting service despite the fact that the motion sensors that are dependable only on a shorter range (e.g., 10 neighbours are switched to full intensity in case of vehicle traffic, 4 neighbours in case of pedestrian traffic). The neighbourhood matrix is initialized based on GPS positions at the time of deployment, and it is further refined and maintained based on traffic characteristics using machine learning techniques. Hence, the real-time control of the lighting system is achieved by distributed intelligence, eliminating the dependence on communication with a central controller.

At the same time, luminaries are monitored and controlled by the central computer. This way, all historic data about the operation of the luminaries become accessible to human operators via a web-based graphical user interface. The dimming levels calculated from motion sensor signals can also be overridden by setting a fixed dimming level, or by defining a dimming schedule on this interface.

Adaptive lighting reduces efficiently the energy consumption of the outdoor lighting system, especially in case of deployment sites with low traffic during the night, such as residential areas or industrial parks.

ENERGY MANAGEMENT SYSTEM

The energy management system comprises photovoltaic (PV) panels and inverters for energy generation, batteries with bi-directional chargers for energy storage, as well as the appropriate measurement and control instruments. PV panels have been sized to achieve a slightly positive energy balance over a yearly horizon, whereas batteries to ensure island mode operation for at least three hours in case of power outages, considering the environmental, meteorological, and traffic conditions of the deployment site. Figure 2 shows the predicted energy and financial balance for the 365 days of a calendar year. It is noted that for certain days the financial balance is negative despite the positive energy balance, due to the difference of the electricity purchase and feed-in prices.

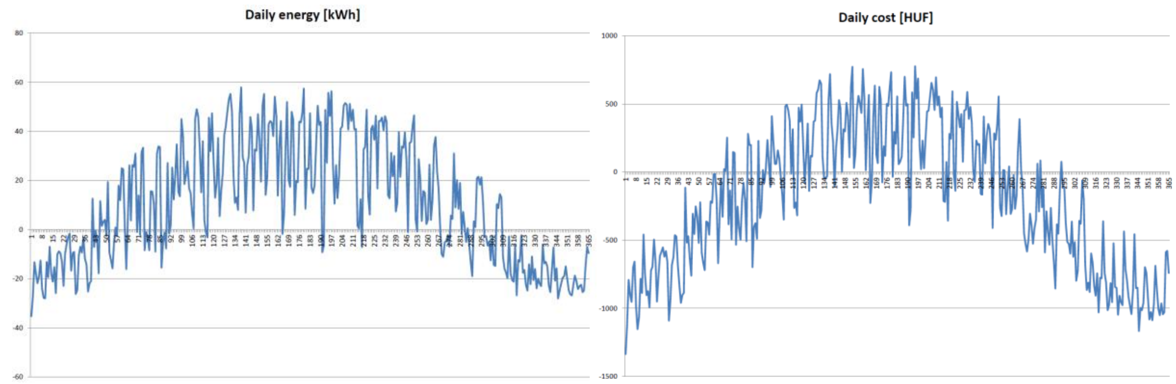

Figure 2. Predicted daily energy balance (left) and financial balance (right) in the E+grid system over a calendar year.

Power flow in the system is monitored and controlled by the central computer, which decides when to buy or sell electricity from/to the grid, with the objective of minimizing the costs of energy (or equivalently, maximizing profit) subject to the applied variable energy tariff.

CENTRAL COMPUTER

The central computer (CC) of the *E+grid* platform is a fundamental component of the entire architecture. It embodies the central control of the application logics and, thanks to its modularity, guarantees an adaptive behaviour of the outdoor lighting system to the environment requirements, by leveraging the configurability and flexibility of the LED light technology and geographic information systems (GIS). The *E+grid* CC has been virtualized into a highly customizable, innovative, cloud-deployed environment. Its minimum software requirements include a web application server and servlet container, a relational database management system, a Java virtual machine and a relatively modern web-browser. The core element of the CC's functionality is a pure Java-based web application, whose main client-server components, and their relative interfaces, have been orchestrated as follow:

a.) **Server side.** The communication between the outer components of the *E+grid* platform and the CC is undertaken by a dedicated layer, responsible not only for handling connections but also for validating and interpreting the semantics between the application logics and the JSON-based communication protocols. Each component is assigned a background job, whose principal objectives are to (i) manage data acquisition and synchronization and to (ii) control the outdoor lighting system by a lighting calendar. The lifecycle management of all jobs running in background is transparently delegated to a scheduler, which is re-definable by the user, under the proper role permissions. Finally, a pool of Java servlets represent the core of the event management dispatcher: any component request accepted by a servlet is then validated and converted into a proper bean, which is, in turn, sent to the specific interface required to process it;

b.) **Client side.** The client-side fruition of *E+grid* services is delegated to a rich Internet application-based graphical user interface (GUI), which embodies similar characteristics to desktop software and is delivered by way of a browser and extensive use of JavaScript. The GUI provides the user with a friendly interface to easily access all of the platform's functionalities, such as the GIS for the installed luminaries (see Figure 3 for further details), user and system administration, the energetic system components management, forecasts and plans analysis and presentation, the overview of events and notifications, luminaries and relative groups management, commands execution, and much more.

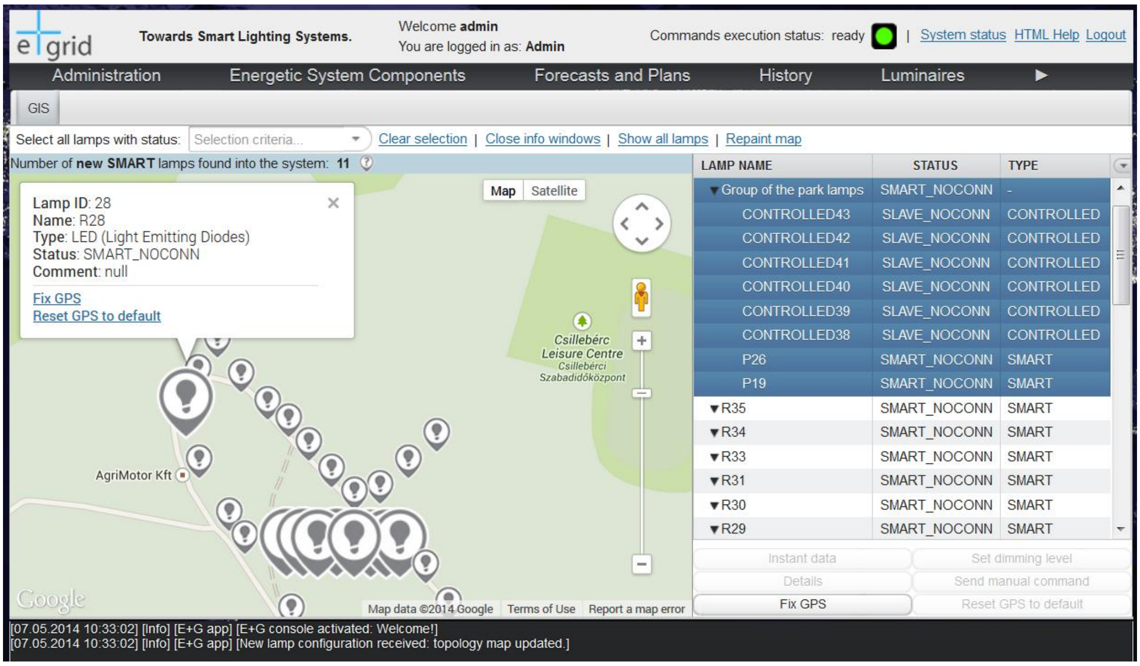

Figure 3. GIS panel of the E+GRID graphical user interface.

In addition to the above, the central computer performs the optimization of the energy flow in the system to minimize the total cost of energy. The computed plan defines when to buy or sell electricity from/to the grid, and when to charge or discharge batteries. Optimization is performed on a time horizon of 24 hours, according to a rolling horizon scheme, with hourly re-planning. The key input data to the problem is the predicted energy production and consumption over this short-term horizon. This prediction is computed from historic data using a discrete time series approach. The models and algorithms used for predicting future production and consumption, as well as for optimizing the energy flow have been presented in the recent conference paper [1].

SIMULATION EXPERIMENTS FOR ESTABLISHING THE BUSINESS MODEL

The business model of the system has been elaborated based on simulation experiments that analyzed the energy and financial balance, as well as the service level achieved by the *E+grid* system on a yearly horizon. The experiments involved 27 different scenarios, each defined by a possible system configuration (whether PV energy production or battery storage is included, the battery technology applied, etc.) and an energy tariff scheme. The investigated energy tariffs included variable (time-of-use) and flat, as well as symmetric and asymmetric tariffs from around the world. For system configurations including battery storage, determining the optimal energy flow in the system is a complex optimization problem. Battery losses depend on the energy flow, hence the solution determines not only the financial but also energy balance of the overall system.

The results of the simulation experiments confirmed that the planned amount of PV arrays ensures a slightly positive energy balance over a yearly horizon, whereas batteries not only provide service level guarantees for the times of power cuts, but can also lead to positive profit by operating the system, by means of trading with electricity to exploit time-of-use tariffs. The detailed results of the simulation experiments have been presented in [2].

CONCLUSIONS

This paper introduced the *E+grid* concept, an adaptive outdoor lighting system coupled with PV energy production and battery storage. The physical prototype system comprising 130 light poles will be put on test in the second semester of 2014 at the research campus of the Hungarian Academy of Sciences in Budapest, a typical industrial park environment.

ACKNOWLEDGMENT

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