INTELLIGENT SYSTEMS FOR ENERGY PROSUMER BUILDINGS AT DISTRICT LEVEL

Angelucci Valerio, Mauri Giuseppe, Urban Renato
RSE – Italy
valerio.angelucci@rse-web.it
giuseppe.mauri@rse-web.it
renato.urban@rse-web.it

Gigliucci Gianluca, Quadrelli Alessandro
ENEL – Italy
gianluca.gigliucci@enel.com
alessandro.quadrelli@enel.com

Claudio Borean
Telecom Italia - Italy
claudio.borean@telecomitalia.com

ABSTRACT

The INTrEPID project aims to develop technologies that will enable energy optimization of residential buildings, both performing an optimal control of internal sub-systems within the Home Area Network and also providing advanced mechanisms for effective interaction with the external world, including other buildings, local producers, electricity distributors, and enabling energy exchange capabilities at district level. For example, by employing the INTrEPID system is possible to balance the energy generated by the PVs with the energy needs of the household and also making it possible for the building to operate off-grid, if weather conditions are favorable. At this scope the INTrEPID consortium has developed innovative software named "smart exchanger" that focused on the management of the energy flow between buildings and the external world. This paper provides an overview of the INTrEPID system architecture, in particular on the smart exchanger technology.

INTRODUCTION

In the latest years, energy optimization has become one of the most widespread challenges in order to face pollutions and climate change problems. For these reasons, renewable energy production is growing year by year, but there are still some problems to be solved as the unpredictability of the energy production by renewable energy sources (RES). The INTrEPID project (www.fp7-intrepid.eu) aims to develop an intelligent energy management system that provides an optimal control of loads, non-dispatchable power generation and storage systems at building and district level (energy optimization) [1]. The intelligent energy management functionalities are the control of electrical loads according to the users' needs and power production forecasts, energy displacement among buildings, and finally set up an interaction between local producers, aggregators and distributors of energy. The energy optimization objectives have been achieved in following complementary ways:

– Developing novel event-based middleware applications that will support advanced monitoring and diagnostic concepts.
– Developing supervisory control strategies**.** Energy use in buildings is optimized as a trade-off between occupants comfort, energy costs and environmental impact, while taking into account people's habits, weather conditions, electrical characteristics of appliances and devices, thermal characteristics of buildings, local energy generation and storage capacities and market conditions, such as existing tariff structures.
– Through the development of an intelligent gateway with embedded logic supporting inter-building energy exchange. This brokerage agent communicates directly with other buildings and local producers to negotiate possible use of the electricity produced locally in their premises.

For this purpose, embedded intelligent systems and middleware technologies for integration of heterogeneous data coming from sub-meters and sensor networks have been developed with the purpose to efficiently monitor and control appliances and sub-systems in buildings, and increase their energy efficiency [2]. These technologies enable optimization at different levels:

– Device-level: optimization of individual devices energy consumption supported by continuous monitoring and diagnostics to detect deteriorated performance.
– Building-level: optimization through the coordinated control of local consumption, generation and storage devices.
– District-level (or neighbourhood level): optimization through the ability to perform energy exchange with other participants connected to the electricity grid.

INTREPID ARCHITECTURE

The proposed architecture for INTrEPID tries to fulfil the needs of current and future large-scale Smart Grid applications. Consequently, its development is driven by the following principles: interoperability, scalability and creation of new market opportunities [3]. Concerning market opportunities, the INTrEPID system develops advanced energy management strategies, which exploit the capabilities of the appliances and subsystems (Energy brokerage module and smart exchanger) and coordinate them in an optimal way while not compromising the desired level of comfort. The solution takes tariff structure and pricing information from the market into account while optimizing the use of energy. INTrEPID encompasses several modules, working together to create the necessary synergies for a functional and effective platform to empower smart grid applications. The *interoperability* between modules and with external entities and/or applications is entrusted to the abstraction created by the communication bus and, when possible, adhering to existing standards. The architecture comprises several building blocks, each of them providing important functions for the other blocks or for the users of the platform as described in Figure 1[4].

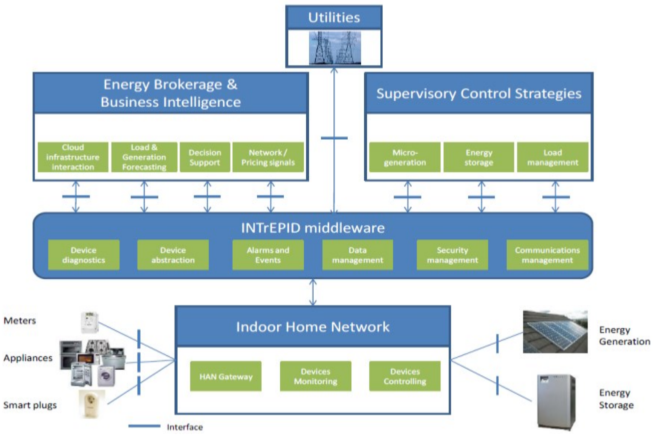

Figure 1: Overall INTrEPID architecture.

INTrEPID also can use multiple gateways for different technologies in each home or building (e.g. one covering smart appliances, another one covering home automation devices, and yet another covering energy consumption and production), which can then be logically aggregated into the INTrEPID middleware and exposed to the control components. These gateways can then be aggregated for combined energy management. Scalability criterion is provided by engineering the interaction between the subsystems, to reduce their complexity and by the use of cloud technologies to facilitate the interactions of subsystems. For this purpose, INTrEPID uses a middleware layer that interconnects INTrEPID technological components: Supervisory Control, Energy Brokerage and Business Intelligence, and the Indoor Home Networks. For the design of the INTrEPID middleware ActiveMQ has been chosen. Additionally, the middleware is based on a distributed publish/subscribe architecture, thus allowing for transparent implementation of distributed applications. A description of the INTrEPID strategies of Supervisory control and business is described in the next subsections.

Energy Brokerage and Business Intelligence

This component provides services that take advantage of the collected historical data. Based on previous consumption patterns as well as load and generation forecasts of the building, Energy Broker provides analysis of the energy use, resulting in feedback and tips on energy efficiency, but also it can make decisions as: about the participation in the energy brokerage (on short term), or about possible retrofits (on long term), equipment replacements and other capital investment actions. Thus, the functions provided by this functional block would be:

- Load forecasting – providing information about expected energy consumption of selected devices, buildings or groups of buildings, based on devices configuration, user preferences, weather conditions and historical data.
- Generation forecasting – providing the expected amount of generated energy based on the generation device model (obtained from the Micro-generation functional block in the Supervisory Control Strategies module), weather forecast and historical data.
- The Decision Support module enables building operators (ESCOs) to make decisions on possible exchange of energy with other buildings

The task for the Business Intelligence functional block is to gather and organize all information available on the platform and to provide support for analysing the data into energy-related reports, dashboards, and alerts. Main functions covered by this block include:

- Data aggregation and processing – preparation of data collected from the buildings and other systems for the subsequent analysis and visualization, e.g. resampling, aggregation, validation and filtering.
- Data visualization and reporting – providing feedback to the end users by evaluating Key Performance Indicators defined for the buildings, helping users to increase their awareness about energy consumption and delivering the insights about their energy use.
- Alerts – by using the Event processing functional block, the Business Intelligence Module can alert users in situations where their energy consumption is experiencing unusual conditions.

Supervisory Control strategies

The objective of INTrEPID is to enable energy optimization in residential buildings and therefore includes control of internal subsystems. A particularly challenging area is local generation and storage. The Supervisory Control Strategies architectural block is represented by an Energy Management System that consists of several functional blocks taking care of necessary functionalities [5]. The energy management system provides the functions for coordinating of local consumption, generation and storage. It consists of 3 main functional blocks – the Micro-generation that monitors and controls the local generation devices, the Energy Storage Management block coordinates the local storage, and the Load Management functional block, which optimizes the amount and cost of energy in the connected homes, as well as in some cases optimizes the energy use at the higher level (micro-grid, district). Regarding the Energy Storage Management, the smart exchanger technology has been developed for the INTrEPID system. This technology permits an increasing of the self-consumption of energy produced by photovoltaics and a reduction of the error between the forecasted power production and the actual power produced by photovoltaics. Next section gives a detailed description of this technology.

SMART EXCHANGER

The smart exchanger is the software component that manages the power exchange between the home electric network and the grid. At this scope, two control logics have been considered. The basic one aims at increasing the self-consumption of energy produced by photovoltaic power plant (PV). The more complex one aims at reducing the error between the forecasted power production and the actual power produced by PV. The first one, is extremely simple, but at the same time very effective, and it permits reducing power exchange with the grid due to an increased self-consumption of the power produced by photovoltaic. The second and more complex control logic is designed to use the storage to compensate deviations between the forecasted PV production profile and the real PV production profile in order to guarantee the expected power output. This requires the presence of an electric storage system (ESS), a PV and three smart meters as shown in Figure 2.

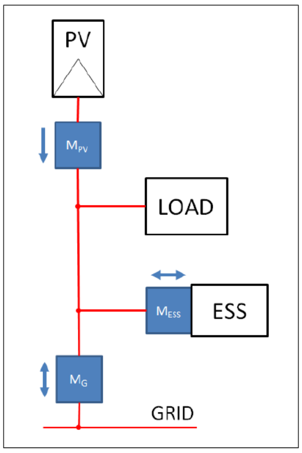

Figure 2: Smart Exchanger electrical configuration.

Meters M_G and M_{PV} are usually fiscal meters provided by the DSO (but they can be simple meters as well), while M_{ESS} is a storage internal meter. M_G measures the power exchange with the grid, and its value can be positive (power absorbed from the grid), negative (power injected into the grid) or equal to zero (no power exchange, i.e. virtual island operation). M_{PV} measure the power production of the PV and can be positive when power is produced, otherwise it is zero. M_{ESS} measures the power exchange between the storage and the customer's electric network and can be positive (power injected in the network – storage discharging), negative (power absorbed – storage charging) or equal to zero (no power exchange). Using the power supply rule, at all times the following equation must hold.

$$\sum P(t) = 0$$

Therefore the expanded equation should be as:

$$P_G(t) + P_{ESS}(t) + P_{PV}(t) = P_{LOAD}(t)$$

With this configuration, there are (at least) three possible usage scenarios for the storage system:

- To improve the self-consumption of the power produced by PV
- To reduce the error between the forecasted power production and the actual power production of the PV
- To follow a desired power exchange with the grid

For these three functionalities, the final aim of the Smart exchanger is to generate a power set-point for the storage. This set-point is calculated starting from the actual measures of the whole power consumption, the PV production, the PV production forecast and the desired power exchange with the grid. The storage system for the experimental setting adopted has been developed by Piaggio. It is composed by modular lithium-polymer battery at low voltage - starting from 1.5 kWh (37V - 40 Ah) - together with modular electrical drives allows managing different sizes of energy. The powers available are 3kW and 4.5kW The basic algorithm used for increasing the self-consumption and decrease the power forecast error are following described.

Power forecast error reducer

The proposed algorithm takes as input the power production forecasts coming from historical data. Another input is the load consumption forecast. The algorithm's main function is power balancing, which has to be done for fixed time intervals. That means the smart exchanger has to balance, using the storage system, the actual PV power production and the PV power forecast according to the load consumption forecast. For each balancing interval (that can be 15÷60 minutes) there is a smaller interval divided into subintervals called control cycle intervals (2÷5 minutes). The control cycle interval serves to estimate the average power production and consumption, and thereby calculate the power set-point for the storage. Quantities managed by the smart exchanger are:

- $E_{\Delta T}$= PV energy production scheduled within balancing interval
- $E_{(\Delta T- \Delta ti)}$= remaining energy to produce
- ΔT= balancing period
- Δt= control cycle interval
- k=previous control cycle intervals counted from the beginning of the balancing period
- $P_{PV\_measured}$ = measured photovoltaic power referred to a specific control cycle
- $P_{PV\_forecast}$ = expected photovoltaic power referred to a specific balancing period
- E_{stor} = energy provided by the storage
- P_{stor} =storage power referred to a specific control cycle

$$\overline{P}_{PV\,j} = \frac{\sum P_{PV\ measured\_k} \cdot \Delta t}{k \cdot \Delta t}$$

Where k is the numbers of previous control cycle intervals and $P_{PV\_measured\_k}$ is the k[th] measured power. At this point it is possible to compute the energy to be produced:

$$E_{(\Delta T - \Delta t_j)} = P_{PVforecast\_i} \cdot \Delta T - \sum_{j=1}^{n} P_{PVmeasured\_j} \cdot \Delta t - \sum_{j=1}^{n} P_{storage\_j-1} \cdot \Delta t$$

Now it is possible to consider the energy that the storage has to provide in the next period in order to compensate errors made by the power and loads forecasts:

$$E_{stor\ i} = E_{(\Delta T - \Delta T_i)} - (\overline{P}_{PVi} + \overline{P}_{stor\ i-1}) \cdot (\Delta T - \Delta t \cdot k)$$

Finally the power set point of the storage in the *i*-th control cycle interval is:

$$P_{stor\ i} = \frac{E_{(\Delta T - \Delta T_i)} - (\overline{P}_{PVi} + \overline{P}_{load\ i}) \cdot (\Delta T - \Delta t \cdot k)}{\Delta T - \Delta t \cdot k}$$

The power set-point can now be sent to the storage system. The algorithm described has been simulated by the RSE team. Figure 3 summarizes results of the simulations in term of power regulation.

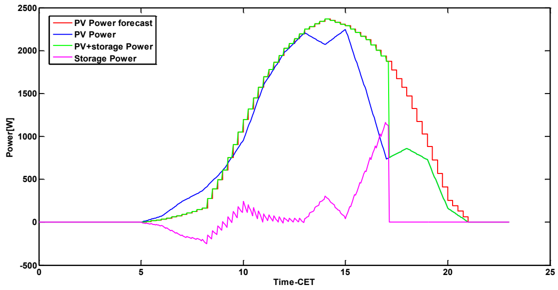

Figure 3: simulation results: temporal trends of the electric power

In this figure, the storage device discharge completely, indeed the regulating power, suddenly drops to zero. Figure 4 shows a comparison between the scheduled energy production and the real energy production. The control algorithm for energy balance has been started from 06:00 CET with a balancing period of ΔT = 15'. The real power at the beginning of every balancing period is compared with the expected power. As a result we have that energy grows until the end of the balancing period. Note that in most of the cases the expected energy has been reached.

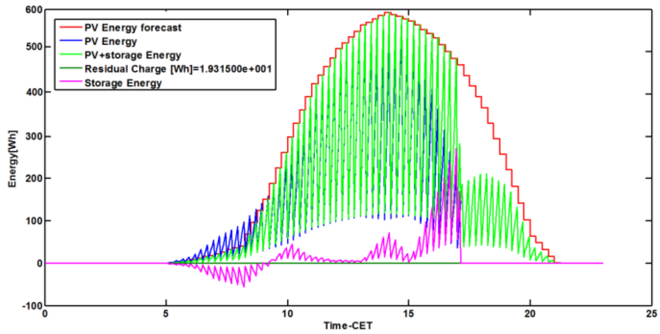

Figure 4: simulation results: storage energy profile

Self-consumption increaser

In order to increase the self-consumption of the building, the electric power produced by the PV is compared with the power consumed by the user. Practically, instant by instant, if the power produced by the PV system is greater than that consumed by the user; the excess energy is stored in the ESS. If the ESS is loaded to its maximum value, the excess energy produced is injected into the grid. When the power generated by the PV is less than that consumed by the user, the missing energy is supplied by the ESS. If the energy contained in the ESS is not sufficient to meet the needs of the user, the missing portion is provided from the grid. With this logic in operation, the ESS delivers electrical energy when the production of the system falls below the consumption of the user. This situation typically occurs in the late afternoon. Figure 5 exemplifies the operation. In this example the size of the storage is equal to 3.5 kWh. As seen, around 17:00 hours of the first day, saturation of the ESS occurs, and therefore the energy produced in excess is injected into the grid. Between hours 19:00 to 23:00, almost all the energy required by the user is provided by the ESS and between the hours 11:00 to 14:00, the PV production can both recharge the storage and meet the user's consumption. Note the constraint on the minimal residual charge that the storage must keep not to be damaged. In order to better highlight the trends, a DOD (Deep Of Discharge) of 95% is considered which implies a minimal residual charge equal to 0,175 kWh. In other simulations a more realistic DOD of 80% and an efficiency of the cycle of charge/discharge of 85% is used.

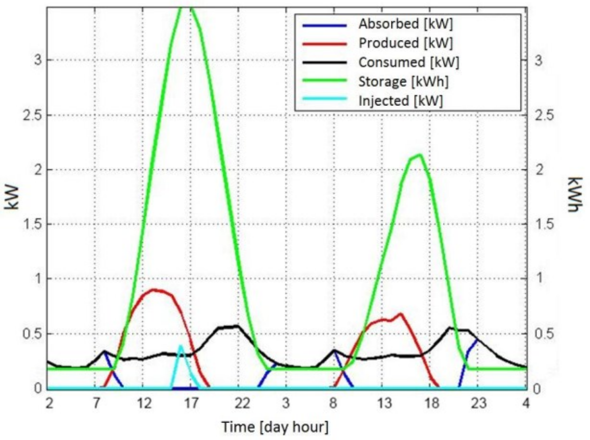

Figure 5: Operating cycle of a smart exchange (simulation).

The algorithm was firstly implemented interacting with a simulator. Both power consumption and PV power production are real data coming from the monitoring of one year (the 2010) of RSE domotic house consumption and production. For the simulation, storage of 3kW of power and 4 kWh of capacity has been used. Also a DOD (Deep Of Discharge) of 80% and an efficiency of 85% were considered. The Figure **6** shows a comparison of the temporal trends, during two days in early spring, of the electric power with and without the storage system. Particularly it can be note how the storage permits to reduce the power exchange with the grid - reducing both power absorbed from the grid and power injected to the grid- and, as a consequence, increase the self-consumption of the power produced by PV.

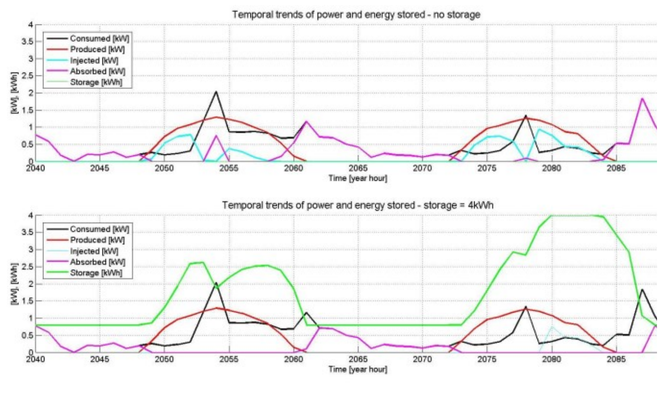

Figure 6: comparison of the temporal trends, during two days in early spring, of the electric power with and without the storage system

CONCLUSION

The innovation introduced by INTrEPID system is that in comparison to traditional home automation and energy management system, there are low additional costs arising from the purchase of additional devices, and there are few installation requirements hence it can be adapt to many different typology of house. The INTrEPID system has been installed on small scale demonstrators and pilots (50 houses), but this platform envisages to be able to support large scale smart grid applications, where the control of thousands of houses, each one with tens of devices, is required. By means of INTrEPID system, different devices on the Indoor Home Network can be aggregated and at district level. Each single user will benefit of a technology that aggregates thousands or millions of customers at the energy point of view. Two technologies are implemented in the INTrEPID system in order to control selected devices. While the Smart Exchanger focuses on controlling a storage system to fulfill the generation profile estimated by the Generation forecast service, the Load Manager is addressing the optimal schedule of the appliance devices. It can control the operation of the schedulable devices by selecting the most effective time to start them within the user defined constraints. Also, it can adjust the set-points for curtailable devices. The major challenge for both components is the uncertainty under which they both need to operate. Most inputs - weather forecast, load or generation forecasts, device models (consumption profiles) and user behavior - have all disturbances affecting the optimal execution of the control system. Addressing these challenges and evaluating the performance in practice is the main task for the pilot operations in this last year of the project.

ACKNOWLEDGMENTS

This project is supported by funding under the Seventh Research Framework Programme – Capacities. The project runs from November 2013 to October 2015 and, in April 2015 the test phase will start in each Pilot involved in the Project. The project involves partners from all over Europe: Telecomitalia (coordinator), ENEL Ingegneria e Ricerca, Ricerca Sistema Energetico - RSE, Gorenje (Slovenia), Honeywell (Czech Republic), Aalborg Universitet (Denmark), Seluxit (Denmark).

REFERENCES

[1] “INTelligent systems for Energy Prosumer buildIngs at District level” – European Commission FP7 –ICT. p 1-3

[2] "INTrEPID: A project on energy optimization in buildings", T. Pedersen, A. P. Ravn, A.Skou, Wireless Summit 2014, 5/2014, Aalborg, Denmark– Paper

[3] "INTrEPID - INTelligent systems for Energy Prosumer buildIngs at District level", C.Borean, M.Sikora, A.Skou, A.Quadrelli, N. Cuervo

[4] “Deliverable D6.2.2: Pilot site description (proposed technology)” p 83 - 92.

[5] “Deliverable 4.5 INTrEPID Supervisory control strategy solution” p 11-15.