NON-INTRUSIVE LOAD MONITORING TO FOSTER NEW SERVICES FOR SMART CITIES

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Abstract—Energy is the foundation block for any socio- economic development. Today, due to population growth and the industrialization of developing countries, we are facing a continuous increase in the energy demand. Improving the strate- gies to generate, optimize and distribute the energy produced is one of the main challenges that smart cities are currently trying to address. New services like demand respond and demand side management are starting to appear, to better manage the production and distribution of energy. Before this can happen, a solid smart metering infrastructure must be built, in order to monitor and give real-time feedback about energy usage. To foster a distributed energy monitoring infrastructure in smart cities, Non-Intrusive Load Monitoring (NILM) may represent the key for both commercial and residential buildings. The basic idea of NILM, suggests using the aggregate power consumption, measured at the utility meter, to track single appliances contri- bution, in order to avoid the need for a sensor for each appliance to be monitored.

I. INTRODUCTION

Starting from the Industrial Revolution, the human devel- opment has had serious impacts on the environment, and the growth and destructive actions of human society have resulted in negative impacts on the Earth's eco-system [2]. We are therefore facing a sustainability challenge where human behavior has to change in order to ensure the ability of future generation to meet their needs.

In this transformation process, cities adopt new technologies to their core system to better manage the use of limited resources. One of the main challenges that smart cities are currently facing [1] is the reduction of energy consumption. Classical electrical distribution systems have been used to transport electrical energy generated at a central power plant to end-users via long-established, unidirectional transmission and distribution systems. These systems have served us well, in many cases for more than a hundred years. Nowadays, along with the increase of the importance of renewable electricity generation, intelligent systems are needed in the electricity market.

Smart grid refers to an improved electricity supply chain based on digital technology that is used to supply electricity to consumers via two-way digital communica- tion. This system allows for monitoring, analysis, control and communication within the supply chain to help improve efficiency, reduce energy consumption and cost.

II. THE ENERGY MONITORING CHALLENGE

Electricity is one of the most flexible and complicated power sources that are available, but unlike most other energy sources, such as oil or coal, electricity cannot currently be stored in large scale volumes in a cost-effective way. This imposes some tight boundaries in managing and producing energy, as the infrastructure must adapt in real-time to different load scenarios with the ability to face the dramatic increase in energy demand every time during the day. This means that power stations, also referred as power plants, must be kept ON all the time also when energy demand is lower than the production capability, leading to resource wastage and pollution generation. With the ability to monitor in real-time the power consumption of single building and by using this information to forecast energy demand, the improvement for the electricity sector would be tremendous.

Just imagine a world where the energy consumption peaks are moved with the availability of renewable resources, ex- ploiting ; where households receive incentive for moving power consumption out of peaks hours or to match the availability of renewable resources, where the cost per kw/h is dynamically adapt based on grid load level or where the energy cost is different based on the load type (i.e., the price for charging an electric vehicle is lower compare to other loads). Before we could achieve these goals, a pervasive Smart Metering infrastructure must be built and integrated with the current systems. Focusing on the residential sector that alone accounts for more than 20% of the global energy consump- tion [9], the only measure of their energy consumption is the bill that they receive up to 60 days after consumption. The bimonthly bill reports the number of kilowatt-hours (kWh) of electricity consumed and the costs that are incurred but is inadequate for managing energy resources, as it does not indicate which loads demands the most energy. This gives no information on how changes in our own choices and behaviors can either lower or offset energy demands associated with changing weather patterns, new appliances, and other electronic equipment.

The dysfunctionality of the current energy measurement system has been recognized for many years. More than thirty years ago, Kempton and Montgomery (1982) described the paradox of consumption without meaningful information as "a store without prices on individual items, which presents only one total bill at the cash register, where shoppers have to estimate item prices by themselves".

It is clear that a solution to this problem is very

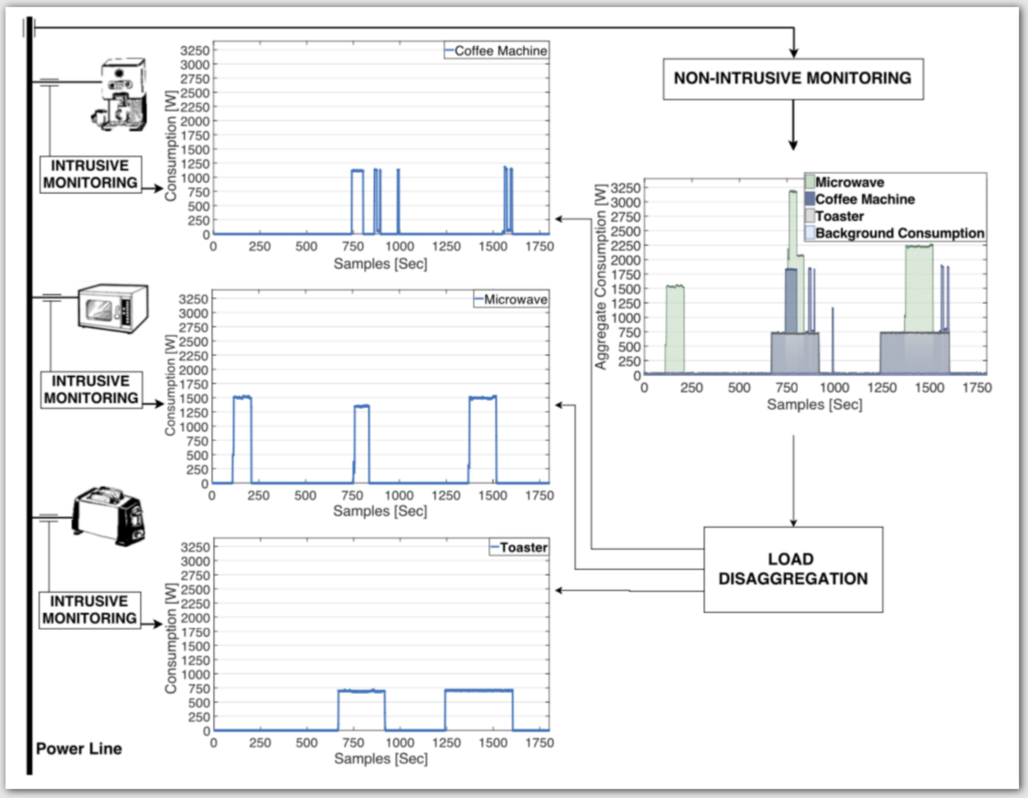

Fig. 1. Intrusive Load Monitor requires a sensor for each appliance we want to monitor. Contrarily, Non-Intrusive Load Monitoring can achieve a comparable result, using just one sensor [5]

is very challenging.

Researchers and Industry have tried different paths for over- coming these limitation, such as smart plugs with the ability to track and monitor the energy consumption of single loads. But this approach is not feasible, mostly due to scalability problems (it requires one sensor for each load and it is difficult to integrate with existing infrastructures).

To foster the development of advanced strategies for the production, distribution and consumption of energy, and also to better exploit the availability of renewable energy, in recent years, researcher effort has moved on the development of a new generation of smart meters, along with advanced algorithm for power analysis, tailored for tracking and monitoring single appliances starting from the aggregate power consumption of a whole building. The ability to track single appliances contribution, starting from the aggregate power consumption acquired by a single power meter, takes the name of Non-Intrusive Load Moni- toring, NILM. This analysis, introduced in the early 90s by George hart [3], can represent the turn key in the energy sector, as it permits to monitor a high number of appliances with just one power meter.

By knowing the contribution of the various appliances, end-users can identify power hungry appliances and they can be motivated to replace those appliances with new and more efficient ones, or to adapt their consumption behavior accordingly. The same data can also be used by the utility company that can offer a new range of services, such as Time- of-Use pricing, to encourage consumers to use less energy during peak hours, to move energy usage to off-peak hours or when renewable energy is available and also implementing strategies for load forecasting that better adapt the production and distribution of energy.

III. BEHIND NON-INTRUSIVE LOAD MONITORING

In the last two decades, Load Monitoring has been an active research area, studied by researchers who investigated algo- rithms that try to discern what electrical loads (i.e., appliances) are running within a physical area, where power is supplied from only one point. Two different approaches can be ex- ploited for monitoring energy consumption: the Intrusive Load Monitoring (ILM) approach, which use one sensor for each appliance, and the Non-Intrusive Load Monitoring (NILM) approach which aims at estimating the load consumption from a unique overall current and voltage measurement. Figure 1 presents the difference between the two approaches.

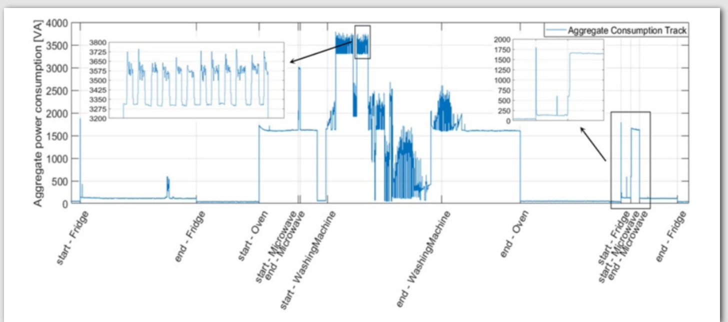

Fig. 2. Different appliances pattern

The idea was born in the late 80’s when George Hart [3] at the Massachusetts Institute of Technology (MIT) proposed using changes in power consumption, as measured at the utility meter, to track the operation of individual appliances automat- ically. Although the proposed approach was appealing, during the subsequent 15 years, NILM studies were limited. Recently researchers renewed the interest as a result of decreasing hardware costs and expanding connectivity infrastructure also stimulated by the governments around the world that have started to put in place action to reduce the global electricity consumption [8].

A. How it works

Non-Intrusive Load Monitoring is the disaggregation of individual appliance consumption from the total consumption, using one, or few more, point of measurement. Electrical loads usually exhibit a unique energy consumption pattern as presented in figure 2. This pattern is usually referred as ”appliance signatures” and enables the disaggregation algorithms to recognize appliances operations from the aggregated load measurements. NILM process, basically involve three stages. Data Acquisition, Features Extraction and Appliance Classifi- cation [6], [7]. Data acquisition is the process of acquiring the aggregated load consumption, sampled at appropriate rate for the purpose of appliance recognition. After data acquisition, the next step is to process the raw data previously acquired, in order to extract the features that characterize the single appliance contribution. Finally, the extracted features are used by suitable algorithms to identify the specific states of the appliances from the aggregated measurement.

IV. SERVICES FOR ENERGY CONSERVATION AND OPTIMIZATION

In the context of sustainable development, many countries worldwide have started to invest in new technologies that can optimize the growing demand for electrical energy. Starting from the data provided by the load analysis, a range of different services can be built to help both end-users to optimize the energy consumed, and utility companies to better manage the distribution and production of energy.

A. Real time feedback for users

Domestic energy consumption accounts for approximately 30% of the total energy use all over the world, and often contribute significantly to seasonal and daily peak demand [9], [10], [11]. However, users often do not have information about how much power devices in their home consume, or even what their overall power consumption is. The only power consumption feedback most residential consumers receive is an aggregate power bill at the end of each month.

The idea behind NILM is simple: help inhabitants to know how much power they are consuming and where that power is going, as providing appliance specific feedback regarding electricity consumption helps to reduce the electricity consumption. The reason for this is that such appliance-specific feedback allows the inhabitants of a household to identify appliances that require a lot of electricity and motivates them to replace these appliances or adapt their consumption behavior accordingly [12].

B. Demand Side Management
Reliable operation of power grid is primarily dependent on perfect balance between supply and load at each given time. It is not an easy task as there is very little control on the demand side (generation side can be controlled according to the load). Controlling and influencing energy demand can reduce the overall peak load demand, reshape the demand profile, and increase the grid sustainability by reducing the overall cost and carbon emission levels. Demand Side Management (DSM) goal is to monitor and implement different strategies designed to influence customer use of electricity. As a result, it changes the time pattern and magnitude of utility's load, encouraging users to consume less power during peak times, to shift energy use to off-peak hours to flatten the demand curve or to follow the generation pattern of renewable sources. There are various DSM techniques [13]. Among other, some of the prominent are load shifting, peak clipping, conservation, load building, valley filling and flexible load, presented in figure 3.

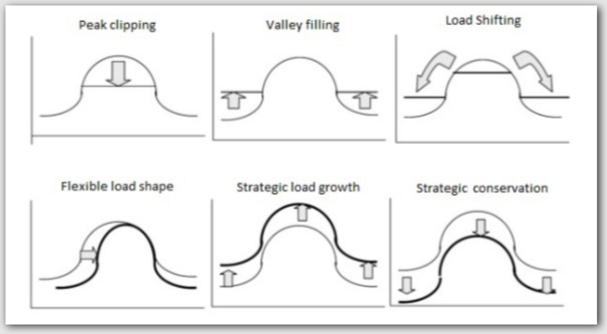

Fig. 3. DSM techniques. Load "shape", representing the demand during time of energy, can be adapted with different techniques.

C. Demand response
Currently end-use customers have no means of receiving information that would reflect the state of the grid, making very difficult to react to variation in energy availability, wors- ened by the spread of distributed renewable energy generation that make impossible to control or request power when it is needed, due to the nature of renewable. In the context of DSM, DR is the willingness to adapt the energy usage to different signal coming from the energy market. The main objectives of Demand response (DR) techniques are reduction of peak load and the ability to control consumption according to generation. In other words, there should be a way for end-use appliances to know and react when cheap renewable energy is available and when there is a shortage of electricity.

The DR mechanism can decrease the cost of the household energy considerably by changing electricity usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time and to better match the availability of renewable energy. Generally, the current DR schemes can be classified into two types: incentive-based and price-based DR schemes. In Incentive-based scheme customers are encouraged to reduce their energy consumption upon request offers from the utility company or according to a contractual agreement, that offers good discount for limited load reduction or shifting. In Price-based scheme customers are encouraged to individually manage their loads by either reducing or shifting their energy consumption from peak hours to less congested hours, by means of time-varying rates that reflect the value and cost of electricity for different time periods. DR techniques would allow customers to participate both saving money and being more environmentally friendly.

Figure 4 shows how energy rate can vary due to availability of supply. The figures highlight how the price rise if the demand is inelastic, meaning that the energy required is fixed. Contrarily, an elastic approach, allows users and producers to adapt the prince, production and demand of energy.

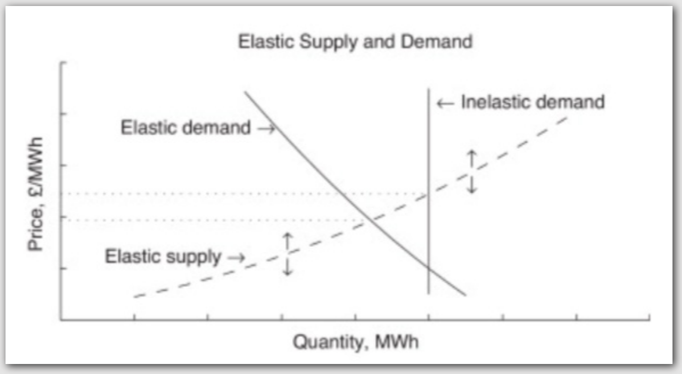

Fig. 4. Quantity/Price relation in an elastic demand/supply scenario.

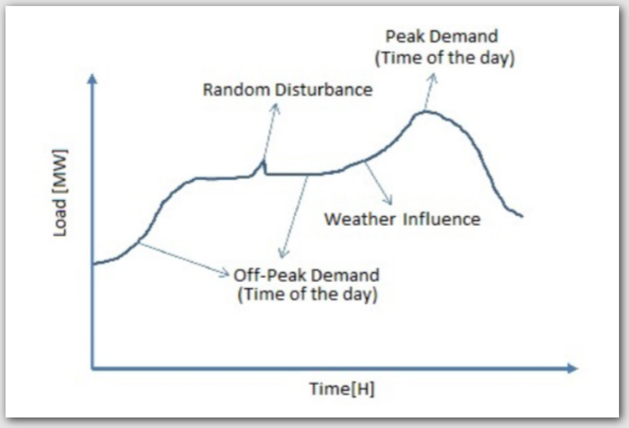

Fig. 5. Grid load variation due to external events. During off-peak hours, grid load can increase by offering lower energy price, while during peak hours increasing prices can lead to a load decrease. Weather can also contribute to increase the grid load (i.e. due to HVAC activation)

D. Load forecasting

Load forecasting is a technique used by utility companies to predict the energy demand in order to balance the grid to achieve an optimal utilization of electrical energy. The accuracy of forecasting is of great significance for the op- erational and managerial loading of a utility company [15], as it permits to better manage power plants and to offset the need for new ones. Conventionally [16], load forecasting is conducted using system level data with little or even no information regarding power consumption profiles at lower levels (e.g., regional level, substation level, transformer level, feeder level, or household level). Better understanding of the actual power consumption patterns of customers is critical for improving load forecasting and efficient deployment of smart grid technologies to enhance operation, energy management, and planning of electric power systems. With the deployment of advanced metering infrastructure (AMI), new energy-use information became available, making possible the creation of distributed energy models, to accurate predict of both the magnitudes and geographical locations of electric load over the different periods of the planning horizon. Different techniques are emerging, trying to find a suitable model that describe the energy consumption over different periods taking as parameters time-of-day, weather, geographic area, period of the year and more recently the data coming from smart meters. Figure 5 show how the grid energy demand varies due to different external events.

V. PRESERVING USER PRIVACY

Smart meters, designed for information collection and system monitoring in smart grid, report fine-grained power consumption to utility providers. With the wide spread of these devices, privacy concerns are rising due to the ability of track inhabitant's behavior, starting from the power consumption patter. User privacy is undermined by the ability to understand which appliance is running in a particular period of time, thus deducing the activities and habits of users, starting from the aggregated power consumption acquired by the smart meters. Therefore, prevention of such adversarial exploitations is really important for privacy protection. To mitigate this problem, researchers have already proposed different solution. In [17], privacy is guaranteed by anonymizing data coming from smart meters and then transmitted to the utility company, while in [18] data is first aggregated and the transmitted, making impossible to associate a specific power consumption pattern to a user. However, such privacy preservation requires either interacting with a trusted third party or requires other households to collaborate, therefore, rendering privacy to be at least partially compromised. To this end, a different approach is proposed in [19] and [20], where load patter is altered to hide the actual electricity utilization within the household. This would ensure privacy preservation even in the case where all measured data are compromised.

Figure 6 shows an exam- ple of this techniques, where consumption pattern is altered through the use of energy storage and local generation [21].
Combining the proposed techniques, end-user privacy is guaranteed making possible the creation of new services based on fine-grained power consumption patterns.

VI. CONCLUSION

Recent increases in the demand for electricity has stimulated interest in monitoring energy usage and improving efficiency. Providing appliance-specific electricity consumption insight enables end-users to identify their saving potential and helps utilities company to better manage the production and distribu- tion. Starting from the information provided by non-intrusive load monitoring approaches, power consumption patterns can be studied and analyzed, leading to an innovative idea for optimizing the grid load, like demand side management, and to provide real-time feedback to households about how they can optimize energy consumption.

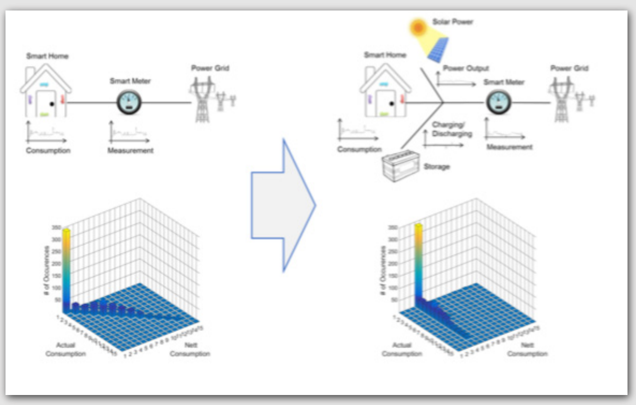

Fig. 6. Consumption pattern alteration through the use of energy storage and local generation

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