



Schlussbericht 15. Dezember 2009

Comparison of energy efficiency solutions for households applying electrical energy measurement of individual consumers

Vergleich verschiedener Effizienzlösungen
mit Einzelverbraucherermessung für Haushalte

Auftraggeber:

Bundesamt für Energie BFE
Forschungsprogramm Elektrizitätstechnologien & -anwendungen
CH-3003 Bern
www.bfe.admin.ch

Auftragnehmer:

Hochschule Luzern Technik & Architektur, CEESAR - iHomeLab
Technikumstrasse 21
CH-6048 Horw
www.ihomelab.ch

Autoren:

Michael Fercu, Hochschule Luzern T & A, CEESAR - iHomeLab, michael.fercu@hslu.ch
Rolf Kistler, Hochschule Luzern T & A, CEESAR - iHomeLab, rolf.kistler@hslu.ch

BFE-Bereichsleiter: Dr. Michael Moser

BFE-Programmleiter: Roland Brüniger

BFE-Vertrags- und Projektnummer: 154370 / 103316

Für den Inhalt und die Schlussfolgerungen ist ausschliesslich der Autor dieses Berichts verantwortlich.

Table of Contents

Table of Contents	3
Zusammenfassung	4
Resumé	4
Abstract	4
Background	6
Goal of the Research	7
Method	7
Results	8
The digitalSTROM (dS) System	9
Commercial Systems (Europe)	11
Geroco Webnergie	12
Plugwise	13
EnergyOptimizers Plogg	16
Comparison	17
Commercial Systems (North America)	17
Academic & Hobbyist Systems	18
Cornell PowerBox	19
Berkeley ACme	20
Tweet-a-watt	21
Comparison	22
Components	23
Developer Boards	23
Powerline Carrier Communication (PLC)	23
Radio Communication	24
Other Existing-infrastructure Communication	25
Measurement & Load Switching	25
Discussion	26
Conclusion	31
References	33

Zusammenfassung

Im Zuge der Suche nach Lösungen zur Erhöhung der Energieeffizienz besteht bei verschiedenen EVU (Energieversorgungsunternehmen) und anderen Akteuren auf dem Energiemarkt eine wachsende Nachfrage nach sogenannten Energiefeedback-Systemen. Diese erlauben es, den Bewohnern von privaten Haushalten deren (elektrischen) Energieverbrauch detailliert zu präsentieren. Dies mit dem Ziel, die Menschen zu sensibilisieren, bei ihnen ein grösseres Bewusstsein für den persönlichen Energiebedarf zu schaffen und sie dazu zu motivieren, Strom zu sparen. In einem weiteren Schritt können diese Informationen auch für eine Automatisierung zur Verbesserung der Energieeffizienz dienen.

Der vorliegende Kurzbericht analysiert existierende und in der Entwicklung stehende Systeme, die in der Lage sind, detaillierte Energieinformationen von elektrischen Geräten und Gewerken im Haushalt zu messen und zu präsentieren und auch gewisse Automationsaufgaben zu übernehmen. Der Fokus des Berichts liegt auf kommerziellen Systemen, die dem Endkunden heute direkt oder indirekt über die EVU zugänglich sind. Sie messen den elektrischen Verbrauch, kontrollieren automatisiert Geräte, stellen Benutzerschnittstellen zur Verfügung, können mit anderen ICT Systemen interagieren und bieten optional erweiterte Dienste an (z.B. über das Internet). Wir haben vier Systeme identifiziert, die den Anforderungen entsprechen und in der Schweiz erhältlich sind. Sie werden im Bericht miteinander verglichen. Darüber hinaus enthält der Bericht Informationen über weitere (Teil-)Systeme und gibt beispielhaft Auskunft darüber, wie man mit diesen ein Gesamtsystem aufbauen könnte.

Resumé

A la recherche de solutions pour augmenter l'efficacité énergétique, de nombreuses entreprises du secteur énergétique (EVUs) et autres acteurs ont une demande de systèmes qui permettent un rétro-signal de l'énergie. Ces systèmes permettent aux habitants de ménages privés de voir leur consommation d'énergie (électrique). En vue de sensibiliser les gens, d'éveiller une conscience pour le besoin d'énergie personnel et de les motiver d'économiser l'électricité. Ces informations sont au service Dans une étape supplémentaire ces informations peuvent être utilisées pour une automatisation afin d'améliorer l'efficacité énergétique.

Ce compte rendu analyse des systèmes existants ou en cours de développement qui sont à même de mesurer et présenter des informations détaillées sur l'énergie d'appareils ménager et qui adoptent des fonctions d'automatisation. Le point de mire de ce récit sont des systèmes commerciales qui aujourd'hui sont accessibles aux clients finals directement ou indirectement par les EVU. Ils mesurent la consommation d'énergie électrique, contrôlent automatisé les appareils, mettent à disposition des interfaces d'utilisateur puis ils savent interagir avec d'autres systèmes ICT et offrent des services étendus (p. ex. par internet). Nous avons vérifiés quatre systèmes qui correspondent aux demandes et qui sont disponibles en Suisse. Ils sont mis en parallèle dans le récit. Au-delà le rapport contient des informations sur d'autres (parts de) systèmes et informe de façon exemplaire comment on pourrait y créer un système complet.

Abstract

In the course of searching for solutions to energy efficiency, there exists a growing demand for so-called Energy Feedback Systems at numerous energy companies (EVUs) and other stakeholders in the energy market. These systems allow the presentation of highly-detailed (electrical) energy consumption information to the residents of the households which the EVUs serve. This is done with the aim to sensitize the people - to provide them with a larger

awareness of their personal energy consumption in order to motivate them to conserve power. In a further step these systems can also be used for automation to improve energy efficiency actively. The market for such devices relatively new and still small but will grow as energy prices rise, systems become readily available, and people become more informed.

This short report analyses existing and near-future systems that can provide this information from, and automation to, household electrical devices. The report focuses on commercial systems available for purchase to utilities or direct to customers. They measure electrical consumption, automatically control electrical devices, communicate with a user interface, may interact with other ICT systems and optionally perform other services of convenience. We have discovered four commercial product systems available to Switzerland that conform to these base requirements, that we perform a side-to-side comparison of in this report. Furthermore, we provide information on other systems, and exemplify the construction of such systems, within this report.

Background

Our society has embraced numerous advancements in energy efficiency and conservation this decade in order to resist energy waste for ecological, political, and even moral reasons. Our energy waste, long ago acceptable due to abundant fuel used sparingly by a small population, has become a growing concern today as supplies begin to dwindle and consumption rises. Energy waste is reduced through better energy efficiency and energy conservation. Energy conservation is the concept of using less energy through either *energy efficiency* or through simply using less energy. To heat a room less and wear a sweater is an example of energy conservation. Energy efficiency is the narrower concept of using less energy to provide the same level of energy service. Energy efficiency may be improved applying advanced ICT that comes in the forms of *smart grid* infrastructure, *smart meters*, *smart appliances*, *energy efficiency portals and labels* (information tools), and many other means. To improve the efficiency of an inefficient device, one can replace the device with a more efficient one, or add a new device to modify the operation of the inefficient device in an automatic or semi-automatic fashion. To improve efficiency and ultimately conserve energy, energy must first be seen and then acted upon. By using the tools for measurement and automation, energy becomes visible (and understandable) and becomes conveniently manageable, and thus can be conserved as a result.

Today the common customer today uses electricity indiscriminately, since electricity is considered to be intangible, always available, and inexpensive. Studies [1] show electrical conservation figures of 10-15% per residence are possible on average for measurement and manual control alone. Electrical utilities have implemented a conservation tool known as “time of use” (ToU) that raises the price of electricity during time-of-day where it is more in-demand; in addition, for high-use customers, utilities have deployed Advanced Metering Infrastructure (AMI) systems that can remotely control/stop a building’s non-essential appliances when electrical consumption on the electrical grid is high. Manufacturers are extending this concept to home *smart appliances*, and by 2012, may give users the ability to delay starting their new washing machine until the cost of electricity is low and even receive a notice of laundry cycle completion; and enabling air conditioners and refrigerators to pre-cool before the time of day when prices are higher. The disadvantages of these appliances include: higher cost of new device, cost of discarding an existing device, the renter’s obstacle of replacing an existing appliance they may not own, lack of interoperability between manufacturer communication protocols, and lack of commercial availability. Smart home components have been able to measure and control electrical appliances for more expensive homes for the past two decades; but the total cost of their external wiring, configuration, servers, and other infrastructure have made them prohibitively expensive: the components alone cost approximately CHF 50-200 per appliance (the same as some appliances).

The newest solution (2005+) to control existing electrical appliances are adapters that, when inserted between an electrical appliance and the electrical outlet, can perform the tasks of *controlling* the device’s electrical supply, *measure* its electrical consumption, and perform other control and communication functions as well, all within the same device. This type of product has only been available within the last five years from ten or so companies. There were only three known commercial distributors in Europe in 2009 and a limited range of products priced between CHF 50-150 for every appliance. These products differ from smart home components in that they are less bulky, require no additional infrastructure, can be easily or self-configured, are single-purpose, and are simple to use. The main interest in this novel technology comes from a limited group of home automation hobbyists and energy utilities but with sensitization and education it is possible that a larger population could adopt them in daily life. Beyond these three systems is a prototype that is currently in development and goes beyond energy management into more complex home automation. These four systems are the main focus of this report.

Goal of the Research

The primary goal of this report is to evaluate and compare potential present or near-future technologies that can undertake the tasks of electrical measurement, load switching, communication, and extend to home automation features, preferably within a single package. Therefore, this research identifies single systems or a combination of several disparate components that can undertake these tasks. On the market today there are already some existing similar solutions, some of which are mentioned in the report of the BFE Project “MEGA” (Project Nr. 102668) [1]. In this study we take a closer look at known systems to see what they provide and then compare their features for various criteria (see *Method*).

We aim to identify systems and technologies that can be used to provide the following four basic features to electrical devices wired into today’s traditional electrical outlets:

- Measurement of the electrical energy consumption of the attached electrical device
- Actuation (switching and/or dimming) of the attached electrical device
- Command-and-control capable network that does not require new infrastructure
- An interface for accessing measurements and performing commands

We also seek to highlight systems and technologies that can provide the following features:

- Centralized control providing remote display, control, and configuration
- Actuation, measurement, and remote control devices that are small and fit as an integrated circuit (preferably by current-sensing, gate-drive HVIC) within a luster terminal or equivalent.
- Remote control of actuation through a (wired-in or remote) switch
- Communications network that is re-usable for other command and control task.
- Centralized control for data acquisition, display, control, and configuration with:
 - an open interface for third-party development (incl. open-source software)
 - an interface that has plug-and-play capability
 - an interface that is accessible using the home’s IP-backbone
 - remote control that has scene support (multiple devices on-off)

Method

The following method was applied to obtain the results described in the upcoming section:

1. Searching for, identifying, and collecting a pool of technologies. Collection is performed through an Internet and literature search.
2. Sorting the collected technologies into three categories:
 - Commercial systems that satisfy the four primary tasks
 - Academic and development systems
 - Other components that satisfy any of the four primary tasks
3. Ranking the complete systems by immediate usability and focus on the most fit solutions for deployment in Switzerland and Europe. The most fit solutions are described in detail by themselves, and with respect to the benchmark system (digitalSTROM, dS).
4. Finally, comparing the fit systems by several criteria in a side-to-side comparison. These criteria are defined as:

Commercial	Product	Name of Product Line or Model
	Organization	Name of Organization
	Market	Marketplace where product is distributed
System	Type	Full System or Component
	Install Knowhow	Level of knowledge required to install.
	Date	Estimated year of when device became public.
	Est. Power	Estimated power for 20 devices, 5 circuits, control.
	Est. Energy	Estimated energy per year in kWh (from Est. Power)
	Share of 2000W	Portion consumed in a 2000W society.
	Share of 5100W	Portion consumed in today's 5100W society.
	Est. Cost	Estimated cost for 20 devices, 5 circuits, and control.
Submetering	Phy. Size	Comparative size of the device.
	Granularity	Measurement location & granularity
	Accuracy	Accuracy of measurement (from smartmeter)
	Processor	Major processing component(s) of adapter
	Power	Power consumption of adapter
	DataLog Buffer	For data logging, size of the buffer
	Socket Type	The type of electrical outlet required
	Reading Rate	Fastest reading speed
Load Switching	Adapter Cost (CHF)	Commercial cost (build cost for academic systems)
	On/Off	On/off switching
	Dimmer	Dimming switching (lamps)
	Scheduling	Devices can be controlled on a schedule
Communication	Threshold	Devices can be disabled if stand-by current detected
	Physical Medium	Transmission medium
	Protocol	Transmission protocol
	Speed	Communication speed
	Frequency	Communication frequency
	Wireless Range	Communication range
Processing	Gateway(s)	Available gateways to other protocols
	Server	Control device needed to operate / display
	Display Interface	Methods of displaying information
	Data Interface	Data interface available
	Extra Features	Extra features available
	Open Sw / Hw	Free, Open-source Software / Hardware available

Table 1: Comparison Criteria

estimates for power and cost are provided assuming that the following model represents the deployment environment of each system: A 3-room apartment with average of 20 devices, per home on 5 separate circuits. The apartment has a personal computer, internet access (based on population: 33% broadband, 43% low-speed, 24% none). The apartment is on the third floor. Sub-metering components mounted on same floor or in apartment. Apartment is rented, so appliances cannot be replaced without land-owner's consent.

Results

Four commercial systems were found to have the best fitness to meet our goals. Here we describe each of these four systems and conclude with a side-by-side comparison. The digitalSTROM (dS) system is chosen as the features "benchmark" and is described first. Second come commercial systems that are designed for energy management and use commercial off-the-shelf (COTS) components. European systems are covered in high detail; and non-European systems are mentioned briefly. Finally, three open and academic systems are described for the purpose of communicating how systems can be built from COTS parts. Finally, we describe technologies which a designer could use to construct such a system.

The digitalSTROM (dS) System

The digitalSTROM[3] system is a prototype created by the spin-off of ETH Zürich, aizo, and three other founders started around 2005-2007. It was designed for the purpose of being an optimal (size, cost) solution for energy management and basic home automation. One part of deployment involves electricians, who can install and configure this system quickly and easily into a housing unit even after its construction. The digitalSTROM system provides all of the features that meet the goals of this report and is programmable to perform new features as well. For this reason, it will be used as the benchmark system throughout the report.

The system is constructed from four categories of components connected in a hierarchy. One embedded *server* interprets and issues commands using the internal (digitalSTROM) and external (IP) networks. Commands are performed through end-points, which are 1cm² *chips* with integrated powerline communication modem, measurement, and load-switching integrated circuitry built for high-voltage applications. Chips can be integrated directly into specific classes of devices, for which they must be optimized and calibrated by power characteristics (e.g. 150W resistive lamp, 300W capacitive stereo). Chips are found in four forms now: wall-switches and plug-in switches for remote control; directly in products or as adapter terminals for electrical measurement & switching. Chips can send messages through the existing powerline at a theoretical 200 bits per second using the digitalSTROM protocol; this communications infrastructure could also be reused to send other types of low-rate data.

The **hardware** components needed by the digitalSTROM prototype fall into four categories:

Name	Function	Benefit
dSS10 (Server)	Server / Webserver	Exposes measurement & control (IP/802.3), can act as gateway, enables data exchange, processes data, acts as webserver.
dSM10 (Meter)	Central measure- ment, communica- tion & control	Designed to be attached to one entire circuit (per room). Per- forms measurement ($\pm 1\%$) and switching of the circuit. Trans- lates data between dS-PLC (devices) and dS485 (server).
dSD2xx, dSD4xx (HV IC)	Distributed meas- urement, commu- nication & actuating	Small measurement and actuation HVICs designed to be wired to lighting (D2xx) and to end-point appliance (D4xx).
dSD5xx, dSD7xx	Remote Control	Switch or dimmer with integrated color-coded LED. Switch can act as normal on/off/dim and can be programmed for scenes.

Table 2: digitalSTROM Components

In more detail:

digitalSTROM Server (dSS10)

The server controls other digitalSTROM devices, performs processing, and communicates externally. Its dS-485 interface communicates internally with dS Meters to receive data, send commands, and handle events. The integrated web server and other IP services are available through an external RJ-45/802.3/IP interface. They can be accessed by client/server model functionality using SOAP and JS/JSON. Aizo provides an application programmer interface (API) that facilitates access to the core digitalSTROM functionalities through the server. This allows a community of developers to write their own applications to expand the functionality of the system, including integrating it with other software for home automation.

digitalSTROM Meter (dSM10)

The meter is designed to be attached to one entire circuit (per room). It performs central measurement ($\pm 1\%$ accuracy) and switching of the entire circuit (16A). It translates data between the dS485 used by the server and dSPLC used by devices in a room. The meters need to be mounted on a DIN-rail by an electrician.

digitalSTROM Chip (dSD2xx/D4xx-series)

The measurement and actuation chip is wired into lighting (D2xx) and to end-point appliances (D4xx). Each chip performs current measurement ($\pm 5\%$ accuracy) and actuation. The chip can be wired into an adapter terminal or embedded within the device itself.

digitalSTROM Remote Control (dSD5xx/D7xx-series)

This is a button, such as a wall-switch or cord-switch. The button is programmable. Pressing the button can act as the normal on/off/dim or an advanced “scene”. Coloured light through an LED provides feedback of the mode.

The hardware components of digitalSTROM are connected in a hierarchy. The system is connected with three networks across three different layers: dS-PLC, dS485, and IP.

- The Server is connected to the home’s IP network by its RJ-45 Ethernet port.
- The Server (dSS10) is also connected to a Meter (dSM10) components (up to 62) using a wired Serial Bus (dS485) at 115200 baud (up to 2-4Mbps). Both are mounted on the same DIN-Rail and use the same serial bus at the fuse box. The dS-485 protocol is available to all members of the digitalSTROM consortium.
- Each Meter (dSM10) component is wired to a circuit in the fuse box. Each circuit is a power line (230V_{AC} 50Hz) that loops through, for example, a room of the house. Each circuit contains several per-device measurement & actuation (Dxxx) chips. The Meter is the master on the circuit, and the chips are the slave devices. Each circuit is isolated from other circuits – messages and related interference stay within a circuit.
- dS-PLC is a powerline technology that operates at 200 bits per second (theoretical). Communication consists of low-voltage pulses of 10-100µs duration at the zero-crossing. Thus, there are 100 zero-crossings every second where two bits are transmitted through the 10-100µs pulse. The latency of these two bits is 10 ms. Message packets use a 16-bit address, unknown payload and flag size, and hamming code for ECC. As an example - if a packet were 48 bits, to transmit the measurement value of five devices to the Meter, 1.2 seconds would be needed.

The important hardware components and their connectivity are described pictorially in the following two figures:

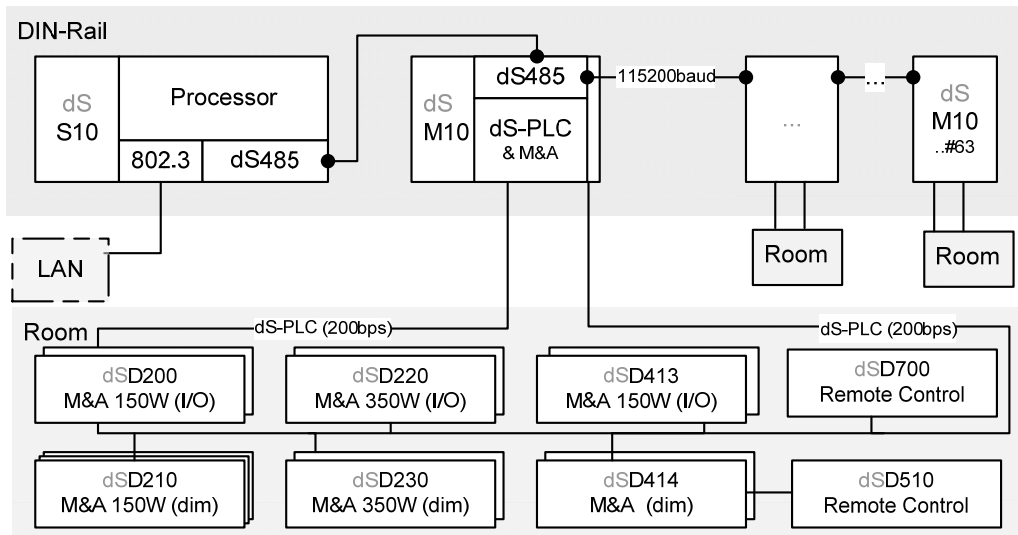


Figure 1: Connectivity diagram for dS, with physical location.

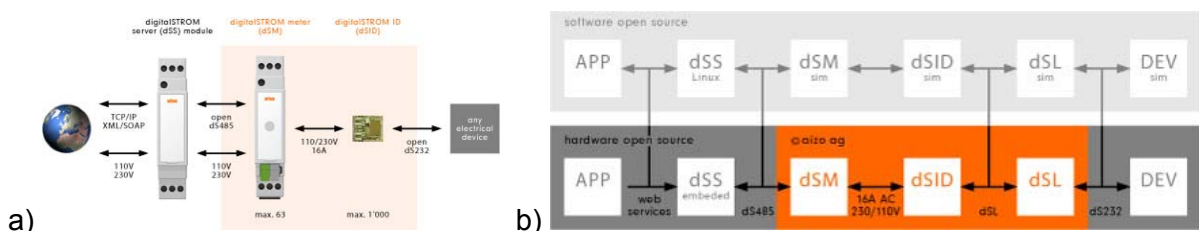


Figure 2: Connectivity diagram (a) by protocol, and (b) by component and licensing

Major advantages of the digitalSTROM system over conventional systems:

- Occupies domain between home automation domain and energy measurement & actuation of existing electrical devices domain.
- Chip size small enough to be integrated within all household devices.
- Low self-consumption. For a 20-device home with 5 circuits, the power consumption would be $20 \times 0.3 + 5 \times 1.5 + 1 \times 2.5 = 16\text{W}$ (146 kWh). This is 0.8% of 2000W.
- Powerline communication that is contained within enabled circuits of the dwelling.

Commercial Systems (Europe)

Numerous commercial systems exist on the market that can achieve these basic goals:

- submetering and switching of one electrical device (or even a group of devices)
- communications network between all end-point devices and a control system
- at least one control point for reading measurement data and controlling on-off switching

Technologies available today for the Swiss or European market were developed up to a few years ago and include Webnergie[8], Plugwise[9], and Plogg[10]. These conventional technologies share a common form and function, as seen in this diagram:

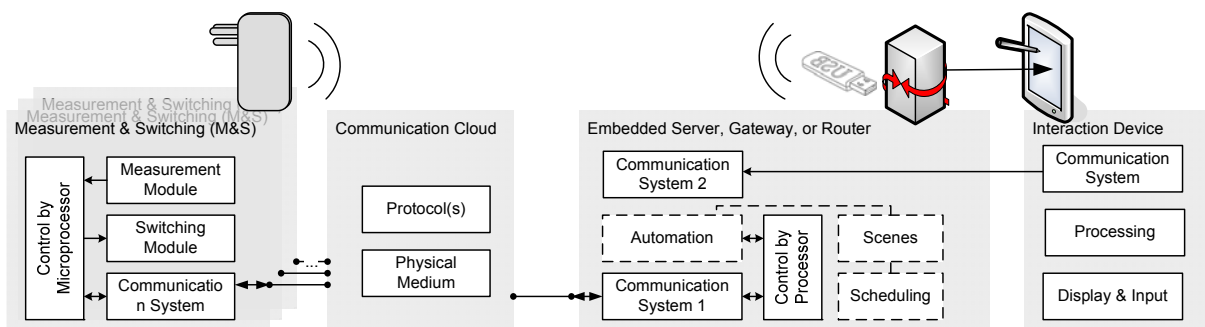


Figure 3: Principle system design

These three share the following features and compare to digitalSTROM in the following way:

- An adapter that is plugged into the electrical outlet; the adapter conforms to the electrical interface and safety specification of the country. Into the adapter is plugged an electrical device (TV, Printer, ...). The adapter measures the energy of the device and can switch it on and off. Switching can only be done by the controlling computer, because none of these adapters have a pushbutton to turn the device on despite schedule. By comparison, dS is either device-embedded or wired in through an adapter terminal by an electrician.
- The adapter consists of a PCB with four circuitry regions: power supply, energy measurement, switching, control and communication. The power supply transforms voltage from 230VAC to 5-12VDC levels. The measurement circuitry consists of a chip (IC) and several high-power-rated passive components that measure voltage and current periodically and use these values to calculate the power consumption. The load switching circuitry is a solid-state 16A relay. The control circuitry is a microprocessor or system-on-chip that controls the relay, performs calculations and storage of received measurements. The communications circuitry uses a chip which is often integrated into a microprocessor package and wired to an antenna-on-PCB. The parts used for design are standard COTS chips; this is advantageous if design must be made quickly by a small team for a small market since parts are individually tested and readily available, but equally disadvantageous in the resulting large design size, cost, power, unused functionality, and a proprietary hardware interface that cannot be easily extended or reused. In comparison, the digitalSTROM chip is designed and optimized for mass-manufacturing, which leads to

a reduction in size, especially for low-power components. The digitalSTROM protocols are also open and allow users to expand the functionality, often for free, creating a more valuable product.

- The adapters communicate using a low-power wireless technology. Often this is a wireless mesh network that uses 802.15.4 and is based on ZigBee (custom profile). They communicate using an openly exposed medium and have limited processing power that decrease reliability, security, and privacy. By comparison digitalSTROM uses a low data-rate power-line communication form that is slower but more secure.
- An USB stick is used to convert between the wireless protocol and a format usable on a PC or embedded computer. Format for addressing the devices is mostly proprietary and closed. A closed-source graphic user interface is provided by the manufacturer. Third-party and open-source software frontend support may also be available for some products. By comparison dS requires a always-available low-power computer that handles data collection and processing.

Geroco Webnergie

The **Webnergie** is a conventional plug-in system currently being developed and tested in Switzerland. The company, Geroco, is a start-up founded with support from Venture Kick in October 2009. The company has developed plug-in adapters, a special USB key, and is now developing a dialogue-based software system to help reduce energy usage in residences. The system will be commercially available in mid-2010.

The three components of Webnergie are described in the following table below:

Name	Function	Benefit
Webnergie PLUG	Measurement & Switching	Swiss 3-prong electrical outlet adapter (220V). Measures room temperature and electrical consumption (prototypical accuracy: 2%). Programmable. Storage of V,A,W,kWh,PF,°C for 4-9 weeks. Load switching (16A). Can program on-off schedules. Adapter consumes up to 0.5W. For 20 devices 10W (0.5% of 2000W).
USB key	Gateway	Routes wireless traffic to USB for Webnergie PLAY.
Webnergie PLAY	Centralized Control (PC Software)	USB-Key connected to a computer collects data from wireless mesh. Software user frontend uses a dialogue-based system. Information for various devices is clustered per room and displayed as a meter. Profiles for several appliances (e.g. television) let the system guess when a device is wasting power (e.g. stand-by) and suggest an action (e.g. turn off from 9AM to 5PM). The application can program schedules and stand-by conditions.

Table 3: Webnergie Components, PLUG and PLAY

The hardware is connected as illustrated in the following diagram. The plug-in adapters are wirelessly interconnected (ZigBee) and accessed from a computer through USB:

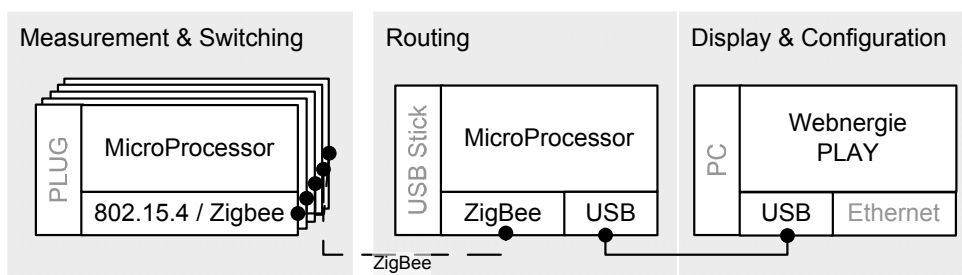


Figure 4: Connectivity diagram of Webnergie system

By comparison to digitalSTROM,

- Webnergie can also undertake all four basic tasks
- Additionally, Webnergie PLUGs can measure temperature, locally store on-off schedule configurations, and buffer energy values for 4-9 weeks without network connectivity
- Can also directly work with Swiss electrical interfaces, like digitalSTROM
- Component reuse through partnerships with home automation companies & groups
- Can be installed by the customer, and requires no electrician
- Includes design to improve customer's communication with the energy provider
- Automatically finds patterns of consumption and provides advice to reduce consumption
- Uses a high-speed low-power ZigBee-based communications network capable of retrieving electrical and thermal energy consumption (up to every second)

Plugwise

Plugwise is a Dutch start-up established in December 2006. The development process took twelve months, and distribution began after eighteen months. The Home Start Kit is available for €124.95 (CHF 190) and includes (1 x Circle, 1 x Circle+, 1 x Stick, 1 x Source). The Plugwise system has several components available, described below.

Name	Function	Benefit
Circle	Measurement & Switching	Plug-in. Energy measurement. Load switching. Data logging. Communicates using ZigBee-based mesh network. CHF 50.
Circle+	Measurement & Switching	Circle functionality, with added functionality of a network coordinator. Same price as Circle.
Stealth	Measurement & Switching	Same functionality as Circle, but in the form of wire-in device. Costs CHF 75.
Stick	Control Device	Directly connects a PC to Plugwise Wireless-MESH. Controlled as a serial COM-port by Source software.
Stretch Lite	Control Device	Gateway from Plugwise Wireless-MESH to TCP/IP. Controlled through TCP/IP network by Source software.
Screen	Control Device	Displays floor plan and energy consumption in rooms. Provides on/off control.

Table 4: Plugwise Components

Measuring & Load Switching: Plugwise Circle & Circle+ (Smart Outlet)

- Load Switching (<16A).
Hardware used: JQX-115F 1C high-power relay (16A)
- Average Power Measurement (once per second).
Current-sensing IC accurate to 5%.
- External interface: ZigBee-MESH Appliance Module (Ember)

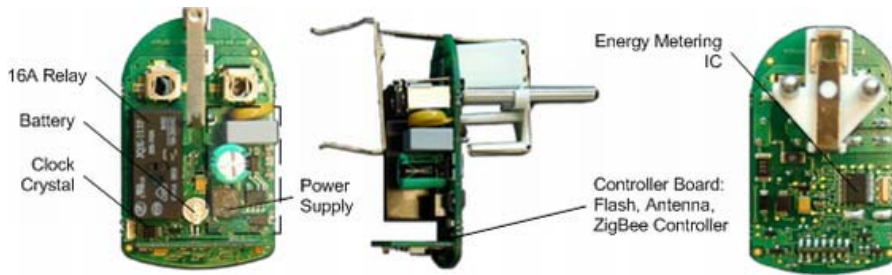


Figure 5: Plugwise Circle (internal)

Centralized Control: Plugwise Stick & Source

- This Plugwise USB Stick is attached to a computer, where it is used by the Source software. The Plugwise Stick connects the PC to the Plugwise wireless mesh network (via Circle+). The Stick is accessed as a serial port (115200 baud) using the closed and proprietary Plugwise command format.
- Plugwise Source is the official software application created by Plugwise. This software can control Plugwise devices by sending commands through the Plugwise Stick. Source includes a single-threaded lightweight web-server that allows control of devices by XML. The server can run as stand-alone or with the attached user-interface. There are third-party user-interfaces such as DomotiGa[16] and HomeSeer can control other home automation components through a partially decoded protocol (DomotiGa) or through the aforementioned server (HomeSeer). There are also example hobby systems as in [17]. It should be noted that the Source software has several privacy and reliability flaws: a copy energy usage data must be sent to Plugwise, there is mandatory registration, and a poorly designed installation process. The official Source User-Interface displays bar-graphs of energy consumption and allows programming on-off schedules and stand-by thresholds (Watts) into the end-points (e.g. Circle), seen in Figure 6.

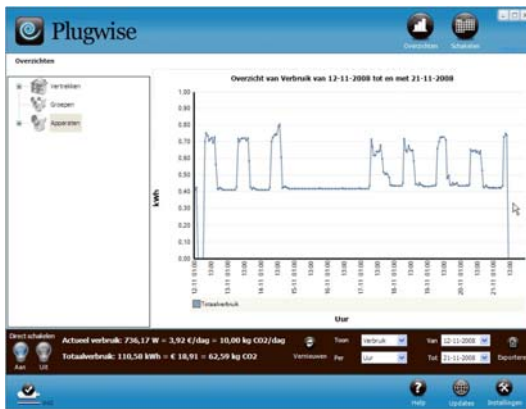


Figure 6: Plugwise Source (Consumption Graph)

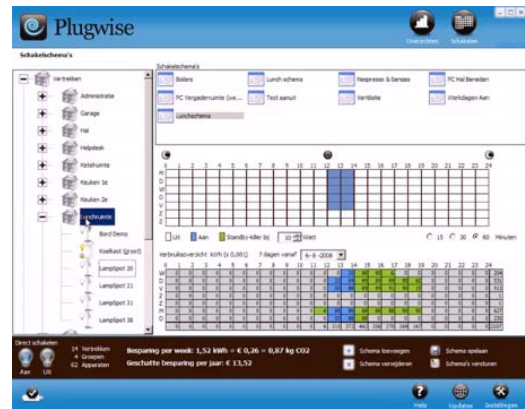


Figure 7: Plugwise Source (Scheduling, Stand-by)

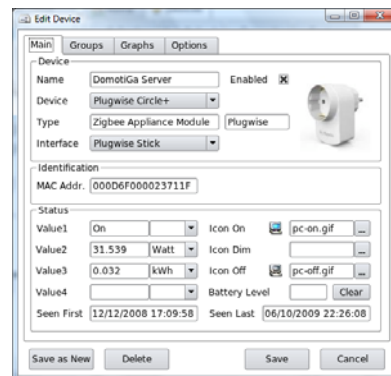
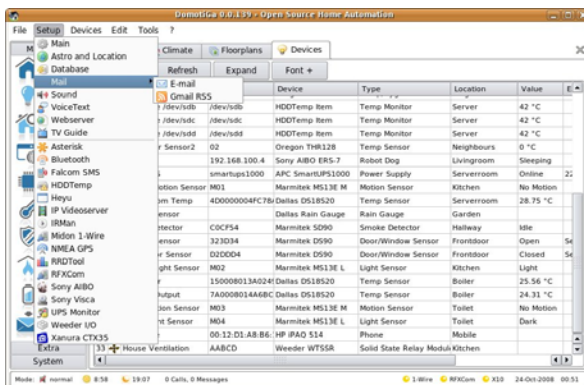


Figure 8: Open-source DomotiGa application (Linux)

Figure 9: Circle adapter properties (DomotiGa)

The Plugwise system is connected by a ZigBee-based wireless mesh network . A proprietary mesh routing algorithm is used. There is one coordinator (Circle+). The Plugwise Stick adapter and Stretch router act as a gateway from ZigBee to USB-serial-port or to IP. Through USB or IP the Source software controls events, configuration, and accesses the end-devices.

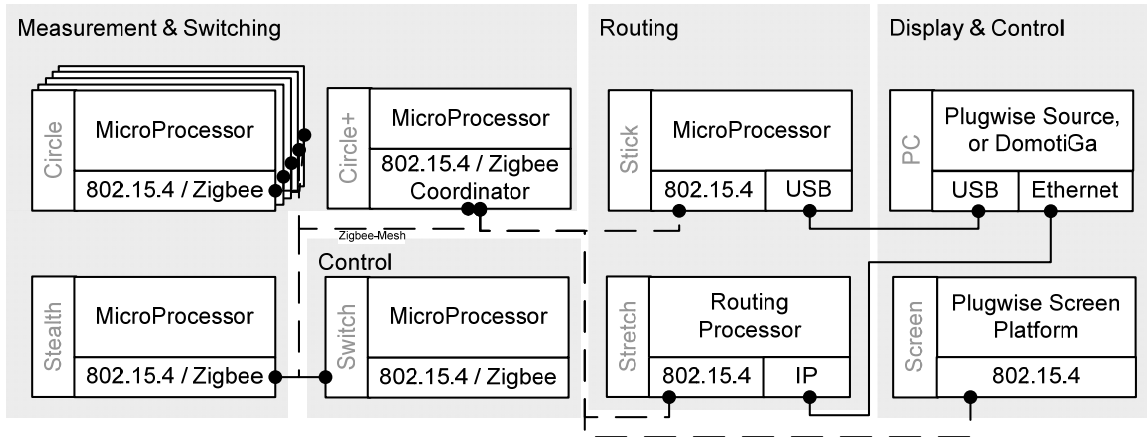


Figure 10: Connectivity diagram for Plugwise components

By comparison to digitalSTROM, this system:

- Has been commercially available on the market since July 2008.
- Can undertake all four basic tasks, additionally can automatically turn off standby loads.
- Has a home automation enthusiast user-base that has integrated this system with open-source home automation software (DomotiGa). Together with other sensors and input devices, this enables rule-based events and scenes. However, there is a cost: the additional power-draw of an always-on computer (15W or more).
- Has a proprietary wireless communications network that is not open or re-usable; but a partially decoded protocol is available at [16].

EnergyOptimizers Plogg

The Plogg system has both a wirelessly communicating plug-in adapter and USB-stick (or IP gateway). A basic software application (Win32) can configure, graph, and debug; and a software API exposes the data to third-party applications. However, there is no elaborate comparison or advice available in the user as with Webnergie or Plugwise. Two academic projects at the University of Southampton and Web of Things Laboratory at the ETH Zürich get information from modified ploggZgb and graph or control it using the Google Web Kit.

There are three components to the Plogg system. The Plogg (ZigBee or Bluetooth), a protocol converter, and the software running on a personal computer.

Name	Function	Benefit & Cost
ploggZgb	Measurement & Switching	Plug-in adapter with energy measurement, load switching, data logging. Communication by ZigBee mesh; can be coordinator. Costs £85 (SFr. 140 per unit, >10 units), £55 (SFr. 90, >500)
ploggBlu	Measurement & Switching	Plug-in adapter. Energy measurement. Load switching. Data logging. Bluetooth. Readable directly by PDAs & SmartPhones using Bluetooth 2.0 (CSR BlueCore BC04 chipset). Costs £55-85.
Telegesis EAP	Communications Device	The Ethernet Access Point is a gateway from PloggZgb Zigbee mesh protocol to IP. Costs £30 (Sfr. 50).
Telegesis ETRX2USB	Communications Device	USB stick. Gateway from ZigBee mesh to PC. Uses the same Ember EM250 SoC as ploggZgb. Costs £35 (SFr. 58).
Plogg-Zgb-ExtCT	Measurement	Plogg with external split core 100A transducer to provide circuit or whole house measurement. The transducer is attached to the live only supply on the load and the Plogg must be connected to the mains supply to provide a voltage reference. £124 per unit.
Plogg Manager	Acquisition & Display	The Plogg Manager is a configuration and debug tool. It sets parameters, retrieves information, can flush information to disk in CSV format (for Excel), and graphs energy data. Free.
Plogg API	Software	The Plogg Application Programming Interface (API) lets developers write their own application by exposing an interface for retrieving and displaying data from the Plogg. Free.

Table 5: Plogg Components

Measuring & Load Switching: PloggZgb

- Electrical interface: Type J (Swiss 10A)
- Load Switching: 16A solid-state relay.
- Average Power Measurement (once per second, single phase).
- Data logging: 5000 samples in 64KB FRAM (83 minutes); stores: kWh, RMS voltage, RMS current, max' watts, reactive power, frequency & phase angle, date & time.
- Processing: 8051-compatible microprocessor.
- Communication: ZigBee-MESH (Ember EM250 SoC with ZNet 2.5)

Comparison

A brief side-by-side comparison of Plogg, Webnergie, Plugwise, and digitalSTROM follows; a qualitative analysis is provided in the discussion:

Commercial	Product	digitalSTROM*	Webnergie*	Plogg	Plugwise
	Organization	aizo & ETHz	Geroco	EnergyOptimizers	Plugwise B.V.
	Market	Commercial	Commercial	Commercial	Commercial
System	Type	System	System	Partial System	System
	Install Knowhow	Electrician	Normal Person	Semi-Technical	Normal Person
	Date	2005	2009	2005	2006
	Est. Power	14W*	10W	-	12W
	Est. Cost	-	1300	2900	1790
Submetering	Phy. Size	Wire-in Chip	Outlet Adapter	Outlet Adapter	Outlet Adapter
	Granularity	Appliance	Outlet	Outlet	Outlet
	Accuracy	±1%*	2%*	±0.5%	±1%
	Processor	dS-IC	-	Teridian 6511	-
	Power	0.5 W	0.3W - 0.5W	-	0.5W
	DataLog Buffer	-	Yes	64K FRAM	512K
	Socket Type	Any (wire-clamp)	Swiss (J), EU	Swiss (J), EU	EU (CEE 7/16)
	Reading Rate	-	1 sec	1 sec	1 sec
	Adptr Cost (CHF)	-	59	100 - 140	50
Load Switching	On/Off	150W (350W) res. 100VA (200VA) ind. No capacitive loads	16A/230V	16A/230W	16A/230W
	Dimmer	✓	✗	✗	✗
	Scheduling	✓	✓	✓	✓
	Threshold	✗	✗	✗	✓
Communication	Physical Medium	PLC	802.15.4	802.15.4	802.15.4
	Protocol	dS	ZigBee	ZigBee	Plugwise Zgb
	Speed	200bps	20 - 240kbps	20 - 240kbps	250kbps
	Frequency	-	2.4GHz	2.4GHz	2.4GHz
	Wireless Range	-	10-75m	10-75m	10-75m
	Gateway(s)	to IP, Web	to USB*	to USB/IP	to USB/IP
	Security	Strong (Physical)	-	Weak	Weak
Control	Server	dSS10 needed	PC for display	PC for display	PC for display
	Display Interface	Web Browser	Web Browser	Win32, WinME	Win32, (Linux)
	Data Interface	Web-based, PnP: Data, Switching	-	ASCII Format: Data, Switching	Plugwise Format: Data, Switching
	Extra Features	70+: Scenes, ...	-	none	Events, Scenes
	Open Source	Partial Hw / Sw	-	FOSS Software	FOSS Software

* Indicates prototypical values. - Indicates unavailable information.

Table 6: Comparison of commercial systems (Europe)

Commercial Systems (North America)

The following systems are mentioned only briefly since they either cannot be used with Swiss or European outlets, are primarily available only to utilities, or are still in development. They would require a redesign effort to be re-usable.

The **Tendril Volt** Outlet is a plug-in adapter (USA, 110V) that measures energy at the electric outlet (within ±1%), switches loads (20A), and communicates using ZigBee to a necessary AMI smart meter. Volt listens for peak-load reduction events and automatically switches a load depending on an A-B-C switch on its side. Outlet data can be viewed using the web-based Tendril Vantage.

EnergyHub is a system that uses wall-socket and power-strip adapters (USA) to measure data and transmit it (ZigBee) to the EnergyHub Dashboard ultra-mobile personal computer (UMPC). EnergyHub is a New York City based start-up (2007) that began trials (2009) with one New York based utility and offers no products directly to consumers.

zerofootprint **TalkingPLUG** is a plug-in adapter (Canada) that can measure energy and switch an attached load. To understand the type of load, it reads an RFID tag (13.56 MHz) that the consumer glues to an appliance's cord, and transmits it (802.15.4) with the energy

values to zerofootprint internet servers, for processing and rendering within their VELO Pulse software. The device is in development (2010), and will cost \$50 (CHF 55) per unit (CHF 1650 for 30 outlets).

The Powerhouse-Dynamics **eMonitor** uses both circuit-level and plug-in adapters to measure electricity values. They are transmitted to a gateway that processes the information and graph it onto a dashboard. This product is in development and is scheduled for release in 2010 (USA). The cost is approximately CHF 620 + CHF12 / mo.

MiCasaVerde is a company established in Reno, NV, USA in 2007 as a lower-end home automation company. They produce a web-based automation controller in the form factor of a wireless router (Vera, 6W, \$300, CHF 310) that accepts a Z-Stick through an USB port. This system can use Euro-plug 300W plug-in lighting dimmer adapters and 10A appliance adapters (both CHF 45) to switch loads, but not to measure energy consumption. Z-wave has no electric measurement devices yet, but relies instead on automatic load switching that depends on a room's Z-wave motion sensors (CHF 50), and Z-wave light switches (CHF 17). Vera claims to have load-management support in the near future, and the Z-Wave alliance is planning to produce a Z-wave electric measurement device in the future.

The **4Home** Energy Network (2009, USA) is a bundled hardware platform for home automation services available only to utilities and telecommunication companies. The platform is based around a Web-based wireless router, the EnergyPoint 3200 Home Energy Command Center with support for TCP-IP (802.3), USB, U-SNAP (Z-Wave-mesh or ZigBee-mesh), 4Home FCML (XML), and has auto-discovery for Echelon ISI and uses a 4Home Sniffer (wireless discovery protocol). Light switches, dimmers, scene buttons, lighting adapters, appliance adapters, and power strips for power management and load switching that support these protocols can be used. An SDK exposes the platform's functionality to the utility and telecommunication's developers for programming.

The **Green Energy Options** (GEO) Duo & Trio is a display that can switch and meter up to 6 or 100 electrical loads using GEO-SAU wall-outlet plug-in adapters. Trio can log data for up to two months.

In addition to the systems commercial systems above, the following systems are not included in this study but were collected and considered:

- Whole-house or circuit-only energy metering systems; these include: Ampy Ecometer, Landys+Gyr P250, Efergy, RateSaver, PowerCost Monitor, CurrentCost, Eco-Eye, Aztech, PowerWatch, AlertMe, Ewgeco, Onzo; YellowStrom/EnBW, Tendril Insight, BreezePlay, EcoDog, and VisibleEnergy.
- Metering-only systems such as Voltcraft Energycount3000 (CHF 20).
- Systems that are designed for high-cost smart homes that require additional wiring. This includes field-bus systems (e.g. KNX-based Promiveo Technology's Energy Monitoring System). Also, systems that require reconstruction or that require the addition of wireless routers or gateways in non-utility owned spaces.
- Systems that depend on the ubiquity of "smart" appliances, such as the Control4 Energy Management System 100 and iControl, are not described; since the appliances they depend on will not be available and installed for several years, and also require support from smart-grid capable utilities.

Academic & Hobbyist Systems

Academic systems provide an insight into how conventional systems are designed. Several have been designed and published by various institutions, including Cornell University's PowerBox (2008), Berkeley's ACme (2007), MIT's Plug (2007), and ICU & Kyoto University's PowerNet (2003). In this report we focus on two, both available in the United States. The Cornell PowerBox shows how to design a metering and switching outlet, including its difficulties and its cost. The ACme system demonstrates the complexity of building a system that is programmable, feature-full, and scalable to the size of an industrial building.

Cornell PowerBox

This PowerBox device was created by two students for an academic project in 2008. This device takes only a few weeks to design, build, and fully test, because of the nature of its simplicity and limited set of features:

- Communication over UART for parameters and measurement retrieval using RS-232.
- Form factor that fits behind a standard electrical socket (US-NEMA)
- Costs CHF 65 for 5 ICs, 5 resistors, wiring, PCB, and two 5V power supplies
- Has an average error of 2.5% for a passive load: 1W error for a 50W light-bulb.
- No power supply or multi-node communication subsystem (wireless or power-line).

A full report on the construction and operation of this system are available at [5].

This system needs two devices to collect and display data: the PowerBox and a computer.

Centralized Control: *Personal Computer*

- Personal computer with RS-232 port, for setting parameters (switching, clock synch., and watt threshold), listening for measurements, and plotting measurements in C#.

Measurement & Switching: *PowerBox*

- Load Switching (< 16A).
Hardware used: Sharp S216S02 solid-state triac-based relay.
- Average Power Measurement (once per second).
Hardware used: Avago HCPL-7520 optoisolated HVIC to output voltage difference over a voltage divider (for voltage measurement) and over a 0.2Ω resistor (for electrical current measurement). Requires additional 5V power supply. Measurement is done 1000 times per second by Atmel MEGA32 to calculate power characteristics, average voltage and current.
- Watt Threshold (automatic switch off when threshold is reached).
Hardware used: Atmel MEGA32 to turn off the relay if threshold voltage is reached.
- Microcontroller unit (Atmel MEGA32) to handle calculation, communication, and control tasks. Transmits information via serial cable (UART / RS-232) to PC in a specific format once per second. Receives information for parameters: switching, clock synch., and threshold.
Hardware used: Atmel MEGA32, additional 5V power-supply, MAX232CP.
- External cabling needed: 2 x 5V power supplies, serial cable.

The building blocks of the PowerBox are diagrammed below: the voltage and current circuitry, the microcontroller, the switching relay inside the box. Outside the box is the wall's raw power connection and output outlet, as well as a serial line to a personal computer, and power supply for the processors and reference voltages. The switching and measurement circuits are diagrammed on the right.

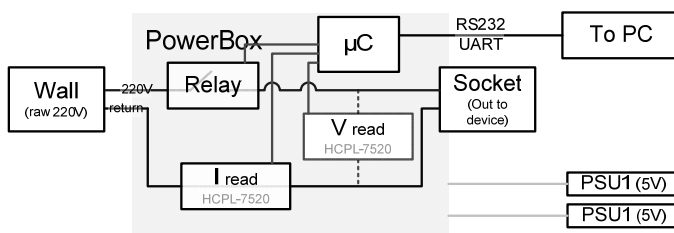


Figure 11: Connectivity diagram of the PowerBox System)

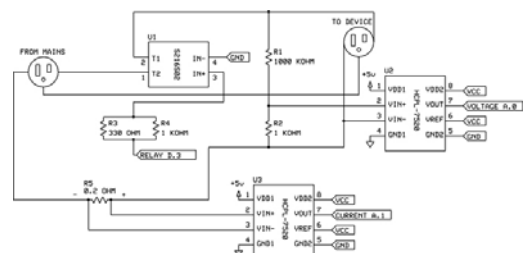


Figure 12: Circuit diagram of the PowerBox

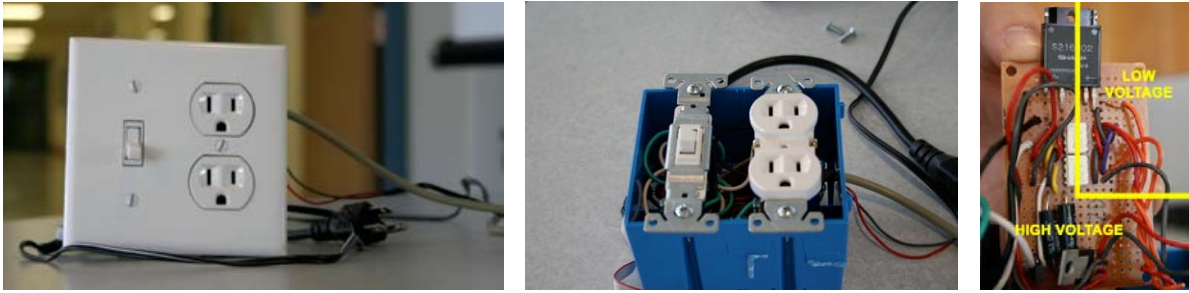


Figure 13: The PowerBox external cabling (left), without faceplate (middle), circuit board and components (right)

Observe that this is very similar to existing designs for measurement and switching. The power supplies that are external in this project can, with some redesign, be integrated on the PCB. Furthermore, a communications method can be integrated:

- as a narrow-band power-line communications modem (MAX299, 10kbps, CHF 10)
- a complete power-line communications modem with UART support (CHF 50)
- as a wireless ZigBee chip (Ember EM250, 20-240kbps, CHF 7.00)

The Berkeley ACme uses a wireless ZigBee chip, for example, for communication, and extends the processing capabilities to IPv6; these details are found below.

Berkeley ACme

The ACme is a plug-in adapter is composed of an on-board power supply, processing, communication, energy metering and load switching. It has many similarities to the commercial systems seen above. It was developed by a group of PhD students at University of California, Berkeley (2007) and deployed throughout the Engineering & Computer Science Building (Soda Hall). The data collected from the 106 wireless nodes is seen on the ACme dashboard at [6]. The design decisions used to design the board are outlined in [7]: power supply, energy metering, communication, control, software interface (API), and ACme applications are described; experimental results are analyzed.

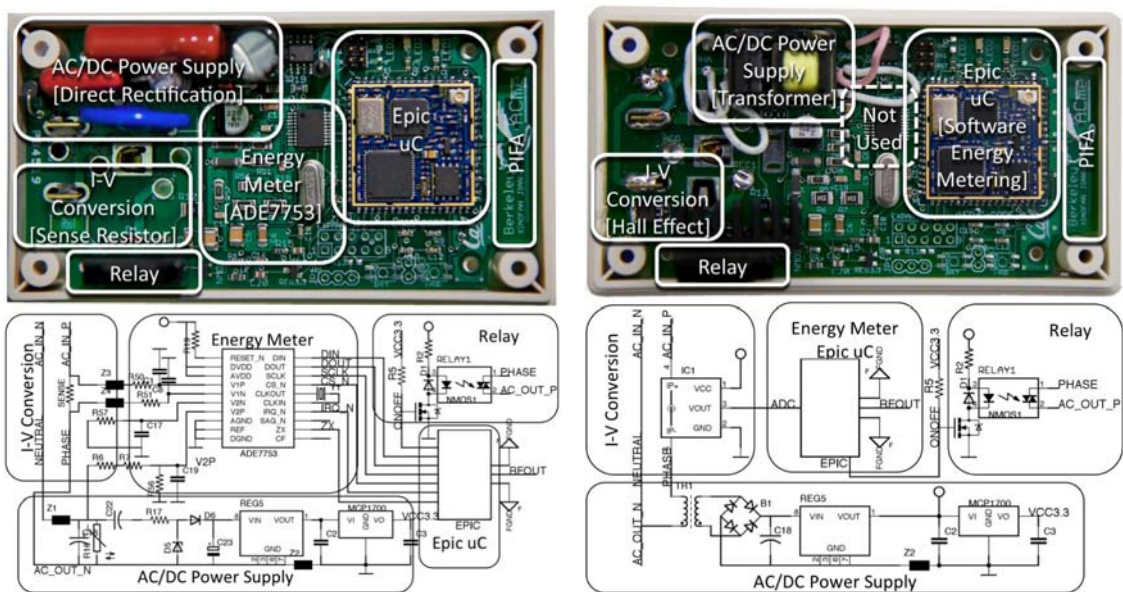


Figure 14: ACme-A with real- and apparent-power IC (left), and ACME-B apparent-power only (right).

Measurement, Load Switching, and Processing: ACme-B (and ACme-A)

- Load Switching (< 16A solid-state relay)
- Average Power Measurement (once per second)
Hardware (ACme-A): ADE7753 Single-Phase Multifunction Energy Metering IC with di/dt Input (Serial-Port Interface). \$2.3 (1000), 3.45 EUR (1).
- Processing and communication.
Hardware: Berkeley EPIC-Core microcontroller platform includes a TI M430F1611 16-bit MCU and TI-CC2420 transceiver. The Berkeley IPv6/6LoWPAN low-power stack (blip) acts as the communication stack. TinyOS is the operating system on the Epic that hosts the IPv6. Each ACme has the ability to run custom software. Example software can be downloaded in a software repository of example applications, compiled, and installed onto the ACme by an adapter. Custom ACmes also exist and include other sensors and controls (light sensors, vibration, light switches).

Tweet-a-watt

Tweet-a-Watt is a modification of a Kill-a-watt plug-in measurement adapter. The Kill-a-watt measurement sensor data (collected every two seconds) is connected to analog-to-digital converter of the X-Bee module. The X-Bee 802.15.4 RF-module transmits the raw data in chunks over the wireless network. Elsewhere a personal computer with a X-Bee module receives the data chunk, then parses and normalizes it, calculates power, and prepares the collective information for graphing. The hobbyist must purchase two components: a \$90 kit and \$20 Kill-a-Watt; and must solder, drill, and assemble together the system.

Comparison

The academic systems presented in the above sections outline difficulty, time and part-cost of designing a plug-in adapter with measurement, switching, processing, and communication capability. Here we evaluate and compare the features of the Tweet-a-Watt, ACme, and PowerBox prototypes versus the digitalSTROM system in a side-by-side feature comparison:

Commercial	Product	digitalSTROM*	Tweet-a-Watt	ACme	PowerBox
	Organization	aizo & ETHz	None	Berkeley	Cornell
	Market	Commercial	Academic	Academic	Academic
System	Type	System	System	System	System
	Install Knowhow	Electrician	Technical	-	-
	Date	2005	2009	2007	2008
	Est. Power	14W*	-	-	-
	Est. Energy	123 kWh	-	-	-
	Share of 2000W	0.7%	-	-	-
	Share of 5100W	0.3%	-	-	-
	Est. Cost (CHF)	-	3450	-	1950
Submetering	Phy. Size	Wire-in Chip	Outlet Adapter	Outlet Adapter	Outlet & Housing
	Granularity	Appliance	Outlet	Outlet	Outlet
	Accuracy	$\pm 1\%^*$	$\pm 0.2\%$	$\pm 0.5\%$	$\pm 2.5\%$
	Processor	dS-IC	Basic PIC	TinyOS / ADE7753	Atmel MEGA32
	Power	0.5 W	-	-	-
	Memory Buffer	-	0K	-	0K
	Socket Type	Any (wire-clamp)	USA (A) 110V	USA (A) 110V	USA (A) 110V
	Reading Rate	-	2 sec	-	1 sec
	Cost (CHF)	-	115	-	65
Load Switching	On/Off	✓	✓	✓	✓
	Dimmer	✓	✗	✗	✗
	Scheduling	✓	✗	✓	✗
	Threshold	✗	✗	✗	✓
Communication	Physical Medium	PLC	802.15.4	802.15.4	Serial
	Protocol	dS	ZigBee App. Mod.	ZigBee	UART
	Speed	100bps	20 - 240kbps	20 - 240kbps	115200baud
	Frequency	-	2.4GHz	2.4GHz	-
	Wireless Range	-	10-75m	10-75m	100m
	Gateway(s)	to IP, Web	none	to internet/IPv6	none
IP / Web-capable	✓	✗	✓	✗	
Control	Server	dSS10 needed	Server Needed	Server Needed	PC Needed
	Display Interface	Web Browser	Open	Many Platforms	Terminal
	Data Interface	Web-based, PnP: Data, Switching	Open Serial Port	Open IPv6	ASCII via UART
	Extra Features	70+: Scenes, ...	-	-	-
	Open-source	Partial Hw / Sw	Published HW/SW	Published HW/SW	Published

* Indicates prototypical values. - Indicates unavailable information.

Table 7: Comparison of academic systems

Components

This section outlines technologies, standards, and commercial off-the-shelf (COTS) parts useful in the construction of energy management systems, such as the ones we have seen above, that we discovered during our research. Measurement, control, and communication standards and the cost of their implementations are listed in this section.

Developer Boards

Several developer boards have recently become available to electronics hobbyists interested in building their own “smart outlet” solutions that can communicate over powerline.



	CuteDigi Audrino Smart Outlet Shield (\$36) Audrino Platform (\$20)	This platform can perform measurement, switching, and dimming.
	LinkSprite Smart Outlet Board (\$50) and Control Unit (\$50)	Can perform measurement and switching. Communication method is UART over PLC.

Table 8: Developer Boards

The advantage of these systems is that hobbyists have the time and interest to spend on developing custom solutions on these boards, and they do not require standardized testing.

Powerline Carrier Communication (PLC)

Powerline carrier technology uses existing power wires to transfer data. Powerlines can carry signals through multiple floors and obstructed spaces; and the power line physical medium is under the legal ownership of the energy utility. Communication over power line depends on low noise and high signal level; and so the quality of the physical line, external disturbances from household equipment, and stray signals from neighbours (filtering) all play a role. In Europe, powerline communication is standardized in CENELEC EN 50065-1. This standard identifies four bands in the frequency range 3 kHz to 148,5 kHz. The A-band is used by electricity suppliers in the carrier range of 9kHz to 95 kHz. B-band is used by consumers without an access protocol from 95 to 125 kHz, and C-band (125-140 kHz) is for consumer use with an access protocol. This 3kHz-148,5kHz range is the narrowband carrier frequency range.

Powerline communication is classified by carrier frequency bandwidth into two categories: narrowband or wideband (broadband). Broadband systems communicate at high frequencies (MHz) and with high data rates (>10Mbps), and are used for VoIP, HDTV, extending LANs, Internet (BPL), and other high-bandwidth applications in the “last mile.” These standards include HomePlug 1.0 / AV / BPL, IEEE P1901 (G.hn / HomePlug GreenPHY), and others. Narrowband systems communicate at medium frequencies (kHz) and low data rates (kbps) and are partitioned into energy supplier and consumer bands. Most narrowband standards and technologies are dedicated to long-haul outdoor communication for electricity suppliers. Fewer narrowband standards are dedicated to in-home communication; these are dedicated to home control and low-speed communication. Narrowband generally has lower power, cost, and speed, and longer range by comparison to broadband systems. For the purpose of home automation and energy management, the ideal powerline carrier technology should be open, low-power, low-cost, low-data rate, and narrowband (CELENEC BC band).

By example, we list popular standards and available integrated circuits that implement these standards below. In-home, narrowband standards in darker color, whereas other standards

meant for comparison are in grey. The focus is on raw data transfer over physical medium, and thus, details for layers above the physical layer have been omitted.

Company	Product	Earliest Reference	Submetering	Networking		
			Granularity	PHY	speed (bps)	modulation
Group	Standard Name (Narrowband)		Level			
1 X10	X10	1975	Outlet	PLC	60	OOK ASK 120k
2 aizo	digitalSTROM	2005	Appliance	PLC	200	ASK -
3 Watteco	Watteco	2005	Outlet	PLC	9.6k	PAM -
4 HomePlug	C&C	2007	Outlet	PLC	0.625-7.5k	OFDM 4.5-21M
5 CEBus	CEBus	2001	Outlet	PLC	10K	SS 100-400
6 HomePlug+ZigBee	Smart Energy Initiative	2009	Outlet	PLC+RF	-	- -
7 Insteon	Insteon (110V)	2004	Outlet	PLC+RF-	2.8-13Mbps	BPSK 131.65k
9 Group	Standard Name (Broadband)					
10 IEEE	P1901	2009		PLC-BPL	14M-200M	-
11 UN ITU-T	G.hn/HomeGrid (G.996)	2009	Outlet	PLC-BPL	1000Mbps	- 24.41k
12 HomePlug	Green PHY	2009		PLC	-	- -
13 HomePlug	AV & AV2			PLC-BPL	189 Mbps	ODFM 2-28M
14 Universal Powerline Association (UPA)				PLC-BPL	200Mbps	- -
15 UPB	UPB	1999	Outlet	PLC	480Kbps	PPM 4-40k

Table 9: Powerline communication standards

Manufacturer	Model	Type	PHY	Networking			Cost [USD]
				speed	band	modl.	
1 Company	Narrowband Communication						
2 NEC	PLM-1	IC	NB PLC	100-20kbaud	50-500kHz	FSK	-
3 Renesas	M306S0FAGP + Yitran IT800	MCU	PLC (HP C&C)	0.625-7.5kbps	9-125 kHz	DCSK	9.4
4 Echelon	PL 3120	Modem	PLC	5.4kbps	132kHz	BPSK	10.8
5 MAXIM	MAX2990	SoC	PLC	100kbps	9-490 KHz	OFDM	11
7 Company	Narrowband Communication (Utility)						
9 Freescale	S-FSK PL Modem	Modem	PLC	2400baud	-	S-FSK	4.45
10 L+G	GridStream PLC TS1/TS2	Modem	PLC	-	-	-	-
12 Company	Broadband Communication			Mbps			
13 iAD	DLC-2B	Chipset	NB HDR	9.6-576kbps	9-490 kHz	OFDM	-
14 ALLNET	Powernet	Modem	PLC (HP AV)	200Mbps	-	-	-
15 MAXIM	MAX2981 / MAX2986	SoC	PLC (HP 1.0)	14Mbps	-	-	-
16 SPiDCOM	SPC200	SoC	EoC (Coaxial)	200Mbps	2-30 MHz	QAM	-
17 SPiDCOM	SPC300	IC	PLC (HP AV)	60-189 Mbps	2-28M	QAM	-
18 DS2	AITANA ++	Chipset	PLC	200Mbps	2-32M	OFDM	-

Table 10: Powerline communication implementations (chips)

Powerline carrier communication is used only by one technology we explored, digitalSTROM. However, various low-end home automation systems have used PLC in the past for simple command and control. They use various communication schemes targeted at digital modulation across the power line, including by using amplitude-, frequency-, or phase-shift keying, by spread spectrum, or by other means. An example of a widely deployed standard, starting in 1975, is X10. This old technology uses an on-off keying (OOK), a simple form of amplitude-shift keying (ASK), to represent data by the absence or presence of a carrier wave, at a theoretical data rate of 60 bits per second. Due to its unreliability several other standards began to appear, especially after the expiration of its patent in 1998. The digitalSTROM technology works by varying the amplitude of the power by 10% at the moment of modulation by shift keying. The theoretical data rate is set to 200 bps at 50Hz (the actual transfer rate is much lower).

Radio Communication

Radio communication is used by the three conventional technologies we explored. In our experience with wireless systems, we have found that communication is relatively reliable, despite interference on unlicensed bands and range-reducing obstructions. For our purpose, a low-power, low-cost, short-range, low-data rate, simple, open specification is desirable. We list relevant and popular protocols here, along with their cost:

Company	Standard	OSI Layers	Earliest Reference	Submetering Granularity	PHY			Networking			Cost Min.
					Kbps	pwr		kHz	range	security	
1 IEEE	802.15.4	1-2	1999	Internode	RF	20,40,250	-	2.4GHz	10-75m	-	\$6
2 ZigBee	ZigBee Stack (SE & HA)	3-4	2001	Internode	RF	20-240	100 uW	2.4GHz	10-75m	AES-128	\$6
3 Z-Wave	Z-Wave		1999	Internode	RF	9.6-40	-	868.42 MHz	30 m	-	\$9
4 EnOcean	EnOcean		2001	Internode	RF	120	(harvest)	868.42 MHz	10m	-	-
5 DASH7	IEO 18000-7		2008	Internode	RF	28	-	433 Mhz	1000m	None	\$10
6 Treshold Co.	ONE-NET	3-4	2008	Internode	RF	38.4-230	-	868.42 MHz	60 m	XTEA	\$ 7
7 Wavenis-OSA	Wavenis	1-2	2008	Internode	RF	9.6khz	-	868.42 MHz	1000 m	-	-
8 Bluetooth SIG	Bluetooth (v 1.0)	1	1999	8-node	RF	1Mbps	-	4.2GHz	1-100 m	PIN, 128-bit	\$6
9 IEEE	802.11 (Wi-Fi)	1	1997	Internode	RF	1-54Mbps	-	2.4GHz	100 m	WEP, WPA	\$6

Table 11: Wireless communication standards (with associated chip costs)

The protocols IEEE 802.15.4 / Zigbee and Z-Wave are often used for this task. The Zigbee Smart Energy Profile (SEP) even defines the packet size and data type for an energy measurement result and can communicate with a smart meter or home area network. The Zigbee Home Automation Profile (HA) also defines the same for switching loads and other home automation features.

Other Existing-infrastructure Communication

Various forms of infrastructure that is found within homes can be reused for communication. These are listed for comparison, and includes telephone wire (POTS/PSTN) and associated ADSL signals, coaxial cable; and in Switzerland, the promise of multi-strand FTTH. One problem with this additional infrastructure the electricity supplier is missing legal ownership of these lines. Other problems include compatibility with the primary form of communication on the medium, and also with the cost of the chipsets and development required to interface over a complex medium.

Group	Standard	PHY	Kbps	Networking range
Group	Standard Name			
1 UN ITU-T	HomePNA/HPNA 1.0 / 2 / 3	PSTN	1-10Mbps	150m
2 UN ITU-T	HomePNA/HPNA 3.1 (G.9954)	Coaxial	-	300 m
3 IEEE	802.3, 802.5 (Ethernet)	CAT5	10M,100M	100 m
4 IEEE	802.11 (Wi-Fi)	RF	1-54Mbps	100m
5 HomeRF WG	HomeRF-WG SWAP	RF	10Mbps	30m
6 KNX	KNX	Fieldbus	1200-9600 bps	1000m
7 C-BUS	C-BUS	Fieldbus	1200-9600 bps	1000 m
8 Echelon	LonWorks (ISO/IEC 14908)	Fieldbus	1.70k-1.28Mbps	1500 m
9 EHS	EHS	Fieldbus	2.4-48 kbps	-

Table 12: Standards for communication over other existing infrastructure

Measurement & Load Switching

There are numerous electricity measurement and load switching products available. Many are listed within [1], and here we briefly review the costs of implementing measurement and load-switching. For electricity metering, Analog Devices produces application-specific microcontrollers for measurement of signals that are single-phase for CHF 1.20-3.70 and polyphase ICs for 4.40-6.70. Other manufacturers, like Teridian (65xx), offer similar products ranging from single ICs to entire Systems-on-Chip. For load switching, examples of solid-state relays that can switch 16A loads include the Sharp S216S0xF (triac or zero-crossing) that can be purchased for CHF 3.40. Thus, the costs per device of using existing relays and electricity meters does not exceed more than CHF 5-10.

Discussion

In the results section, several per-consumer energy management systems were identified. The features of these systems were evaluated and classified for the purpose of comparison with attention paid to relevant system features. Furthermore, components were identified for the purpose of putting together a holistic view of what components are needed today for the construction of these systems.

In this section, we first discuss at a high-level view various advantages, disadvantages, and limitations in design of the four commercial systems available in Europe today or in the near future. Second, we discuss and go into low-level detail on these three points as we analyze various aspects of these systems.

Listed below are significant advantages & disadvantages of the features of these systems:

Name	Advantages and Disadvantages
digitalSTROM	<ul style="list-style-type: none"> + Full, embedded system, with many home automation features + Open-source software and web-interface for programming new functions + Open-source hardware specification may mean 3rd party contributions + Integrated circuits about fifty times smaller and without bulky wall-plugs + No running PC needed to collect data and process commands + No wireless interference + Embedded server has many extra home automation features <hr/> <ul style="list-style-type: none"> - Presently unavailable - Initially requires an electrician to install components - Chip failure may be a burden to replace - Slow PLC communication interface
Geroco Webnergie	<ul style="list-style-type: none"> + Easy to use web user-interface available from manufacturer + Stores most recent information on device until it is collected + Provides thermal measurements for measuring space heating + Swiss 3-prong electrical outlet, no electrician needed <hr/> <ul style="list-style-type: none"> - Advanced automation features require an external server with USB - Unavailable until mid-2010
Plogg	<ul style="list-style-type: none"> + Available today, for purchase online + Stores most recent information on device until it is collected + Free software API for communication with the device <hr/> <ul style="list-style-type: none"> - The only graphing application is the debug tool - Difficult to use and install by non-technical user - Advanced automation features require an external server with USB/IP - More expensive than Webnergie or Plugwise
Plugwise	<ul style="list-style-type: none"> + Available today, for purchase online + Stores most recent information on device until it is collected + Programmable scheduling (and stand-by load triggering) + Protocol already used in a variety of open-source projects <hr/> <ul style="list-style-type: none"> - Advanced automation features require an external server with USB/IP - Euro-plug only. Adapter is needed for Swiss (Type J) plug.

Table 13: Major advantages and disadvantages of top 4 systems

Looking at the table above it becomes clear that digitalSTROM has unique features the other products cannot deliver. But there are also some challenges to the implementation of these features that have yet to be proven to be reliable enough for deployment into products for the mass market.

In this second, upcoming part, we try to relate the complete systems seen above to others or just parts or aspects of what we have seen thus far. We discuss all observations with digitalSTROM as the benchmark.

- **Integration:** digitalSTROM's idea to build an integrated “all-in-one” chip to measure differences in consumption, switch and communicate is still unique. It makes the “client-part” (dS-Chip) of the system very small, easy to integrate and, if really produced in large quantities, cheap. However, to build such a high-voltage chip, which combines all those features on one die is from a technical point of view and considering certification issues – a very ambitious task which yet has to be mastered by the developers of dS.
- **Communication:** dS introduces its own PLC technology. The other systems listed in the table all use the same wireless communication technology (IEEE802.15.4/ZigBee) designed for in-home communication. PLC seems to be the most obvious choice for such a system. Both wireless and PLC have their advantages and drawbacks. However, the main requirements of “no need of new wires” and “easy to install and retrofit” are met by both types of systems. What else characterises PLC and wireless technologies?
 - Both are, compared to dedicated wires, quite unreliable in the home environment.
 - The proprietary dS-PLC technology is, with 200bps, significantly slower than all other wireless and PLC variants. That really only makes it suitable for restricted measuring and control tasks.
 - The dS-PLC uses a patented current (load respectively) modulation which is only active during the zero-crossing of the 230V sine wave¹. That is what makes the communication slow but (according to dS) more robust and makes the integrated chip's area much smaller² and the measurement very compact when compared to “conventional” PLC-systems which modulate a signal onto the sine wave (e.g. using OFDM).
 - A lot of the other available in-home PLC systems are intended for the transportation of broadband (LAN) data and consume way too much energy for our tasks. Some upcoming technologies that could close the gap (low-power, low-cost, quite fast, quite reliable) are being developed (e.g. Wattco WPC, HomePlug C&C) but not yet ready to enter the market
 - PLC is said to produce less emissions (electro-smog). But it does so regardless, as with any technology where current floats through wires. As for IEEE802.15.4/ZigBee, it is to say that it is an optimised low-power technology (default 1mW) that lets the nodes sleep if necessary and minimizes the traffic sent over the air whenever possible.
 - An often cited drawback of IEEE802.15.4/ZigBee is that it operates on the ISM Band on 2.4GHz. This frequency is also used by the popular WLAN (WiFi) and Bluetooth technologies which may lead to interferences and data loss over the wireless link. However, field measurements have shown that, considering some rules, these ZigBee works well for automation tasks in households. Actually ZigBee is one of the technologies of choice for many smart metering companies. The same is true for the argument that systems working on lower frequencies (433 MHz, 868 MHz) are physically better suited to cross larger distances and penetrate through walls. In theory, that

¹ The mechanism varies with the data direction. So the physical communication is not symmetric, which is also due to the fact, that the dS Chip has less resources at its disposal than the meter (server). The dS-Chip modulates the communication signal by increasing/decreasing the resistive load of the consumer attached near the zero crossing for some microseconds (direction Client to Server). The meter realises the signal over short circuits (direction Server to Clients).

² dS does not need coupling transformers etc.

- statement is correct. But again field tests have shown that 2.4 GHz systems do the job, especially if the upper layers allow routing and full mesh networks.
- Besides the wireless and the PLC systems, there exist different flavours of bus systems mainly used in commercial buildings and the luxury segment in the residential area (KNX, LonWorks, LCN...). The main drawback of them is that the initial costs, the configuration and the operation are relatively high considering their use in private households. They are also not suited for retrofitting.
 - **Embedded:** dS provides an embedded environment including small integrated client components, an accurate (central) meter and a web server with an Ethernet interface. This means, no external USB component and a running PC-based server is needed to collect and present the data. Advantages and drawbacks:
 - Embedded:
 - New components for the server need to be introduced and installed
 - The server collects data 24h/365d as it is always on. The same is true for automated switching and control tasks
 - An always on server also always consumes energy. So it should be built very efficiently
 - For the presentation a PC is needed anyway
 - PC-based:
 - Almost every household has nowadays a PC, so no “new” components are needed for the server
 - The PC only collects or is able to execute control tasks data if it is on. And in this case it uses significantly more power than any embedded device
 - The PC is data collecting-, storage- and presenting-device in one. And it does these things very well (e.g. much more performance and memory than an embedded device).
 - **Measurement:** dS only uses the client components (dS-chips) to roughly detect changes and fluctuations in the energy consumption (current variations respectively) of the attached load. To obtain the final energy value it uses the central, more accurate Meter to measure and assign consumption on a per-consumer level. The advantages are that - compared to the other systems with clients (plugs) containing the whole measurement circuitry - the (numerous) dS-client devices become cheap. The dS-Meter measures with an accuracy of 1% up, which is reasonably accurate³. However, the mechanism of a central measurement and assignment of the load change to a specific load is a non-trivial task and dS has yet to prove it to be reliable enough. Other systems use commercially available metering chips [1] or relatively simple current measurement circuits. A second type of measurement system one mainly finds in building automation is in newer KNX actors able to measure current. These are relatively expensive (CHF 200 per outlet), not very accurate and not suited to measure small loads (e.g. measure stand-by consumptions)⁴. Other restrictions that apply to all observed systems:
 - No system is able to measure of poly-phase appliances, some of which are the really big consumers in a household.

³ In an earlier specification of the dS Meter there was a statement about an accuracy of +/-2W that is linear over the whole measurement range of 3600W. However, this statement can no longer be confirmed.

⁴ Feller gibt für Ströme unter 1A eine Genauigkeit von +/- 100 mA, für Ströme darüber 8% an. Der Messbereich liegt zwischen 0.25A...16A

- It could not be clearly determined out of the study how the measurement systems cope with non-resistive (inductive, capacitive) loads.
- **Switching:** Although all systems are able to switch a load on and off, only dS and actuators of commercial building automation systems have a dimming feature. As stated, dS does the switching directly on its chip, the other systems rely on solid state (or electro-mechanical relays) for this task. However, when the load gets too big (>150W/100VA optionally >350W/200VA), dS also needs to revert to relays for switching. It's not quite clear what the dS switch does in case of a short circuit or if the attached load is just greater than the specified maximum.
- **Control:** All systems have some sort of scheduling mechanism to control the attached loads.
 - Whereas loads in the “conventional” systems can only be switched over a PC or by removing the plug, dS also provides user control components (light switches), that may even support more than just on/off functionality (dimming, activation of scenes, simple configuration tasks).
 - dS also supports the configuration of “scenes” in which a certain state of the devices e.g. in a room can be stored and reproduced later on (“go to sleep”, “watching movies”, “eating”, “working” etc).
 - The dS concept of an integrated home automation system that may also interact with other devices such as HVAC, jalousies, security, safety and audio systems is unique and goes far behind just switching loads. However, for this to work, the dS-Alliance heavily relies on strong partners that integrate the dS-chip into their products and provide support for the dS-protocol.
- **Installation & Plug and Play:** All products discover the network nodes and build up the communication network without any further human assistance.
 - dS has the unique feature of being able to identify the type of load that is connected and therefore may try to automate device identification and binding tasks. Binding of devices (e.g. which light switch is logically wired to which lamp) is still one of the most expensive and time consuming tasks in setting up building- and in-home networks. With dS, if there is just one lamp and one light switch in the room, these can be identified and automatically configured. The talkingPlug has a similar feature that uses an integrated RFID reader.
 - If setups get more complex (and they will), a PC based tool and the concept of “virtual” groups becomes necessary to do the configuration and binding in dS.
 - The dS-system needs to be installed by a certified integrator, which is not necessarily needed for the other systems.
 - Field buses of commercial building automation systems still need technicians, network specialists and engineers for the planning, installation, integration and configuration.
- **Interfaces and Extensibility:**
 - As for the hardware interfaces dS provides an RS485 interface to access the meter components and connect multiple of them. Furthermore, the server provides an Ethernet interface. The wireless systems use the IEEE802.15.4 standard and may therefore be accessed through other IEEE-compliant devices. Here, the server components are connected via an USB dongle.
 - On the communication link connecting the clients with the server, all systems use proprietary protocols. Although ZigBee has developed standardised ways (ZigBee Profiles) for measurement and control, none of the wireless systems uses them.

- dS intends to publish the API and the server software under an OpenSource licence. Protocols for the other “conventional” systems have been reverse engineered but are not officially open.
 - The dS server component provides a web server and object oriented SOAP & AJAX/JSON APIs to access the server and the system from other devices (e.g. a PC).
 - In dS, the presentation is done using a browser accessing the web server or a (not yet existing) PC application utilising the provided OpenSource API. So far, only a simple web interface has been implemented. The “conventional” three systems are bundled with a PC application and USB stick to display data in tables and graphs.
- **Data Collection and Processing:** In dS, a central unit (web server) collects the data and does a certain amount of processing for the presentation. There is no information on the memory available for the collected data on the dS meter, but the “conventional” adapters can store several weeks of data (thousands of samples) in memories of limited capacity. Most of the other systems seen so far need a running PC to collect and process the data. The server may collect this data at some point of time after the actual measurement. In terms of intelligent processing, evaluation and interpretation of the values, none of the known systems, excluding the Webnergie, go very far (e.g. giving valuable tips).
- **Security, safety, and privacy:**
- Because of the physical layer, the dS-PLC system is more secure than the wireless systems. The dS architecture prevents the signals from leaving a housing unit. This cannot be guaranteed in wireless systems. Physically accessing the wires and actually sniff for the data traffic is generally harder in wired than in wireless systems. This means that a properly equipped, educated, and interested person could listen to or control this system from a nearby location with relative ease.
 - On the upper protocol layers, not a single one of the systems appears to encrypt or authenticate the data payload. As security normally introduces overhead, dS itself does not seem to be very suited for strong security mechanisms. But of course, they can be implemented at an application level. As for the wireless systems which are all based on IEEE802.15.4/ZigBee, the lack of security is the designer’s choice, since these technologies have built-in support for extensive security features. Overhead, complexity, configuration issues and (in our opinion) underestimated privacy concerns may have been the reasons to not configure these devices to use them.
 - All of the protocols support some kind of error detection or forward error correction. Unintended actions (as with X10) are theoretically impossible.

Conclusion

This goal of this report is to evaluate, compare, and discuss systems primarily suited for per-device metering and control of household electrical consumers/loads, and secondarily suited for automatically controlling attached loads (remotely). Toward accomplishing this goal, a search has been performed to identify and list solutions that conform to a list of criterion desirable in such systems. The results of this search, enumerated in the Results section, provide a side-by-side comparison of four systems: digitalSTROM, Webnergie, Plugwise, and the Plogg. In addition, several systems that aid in the understanding how such systems are constructed and several discovered components that can be used to construct such systems, are also provided in that section. An analysis of the four resulting systems is provided in the discussion section; in this section we summarize these findings.

Concentrating on products intended for private households in Europe, we have encountered three major classes of systems:

1. digitalSTROM
2. Wireless systems based on client parts in the form of plug-like measurement/switching devices and a server part that comes with an USB dongle and software running on a PC.
3. Wired building automation systems

Looking at the findings, we can conclude that there is still no complete system that can provide what dS promises. dS with its features still resembles the benchmark to which the other systems have to compete against in the area of energy efficiency solutions for private households applying electrical energy measurement of individual consumers. However, dS is not yet released for extensive tests, and its operation, simplicity and reliability needs to yet be proven in the field. But if dS comes out for commercial use as promised in the roadmap (Spring 2010) and if the dS-Alliance gains enough support, and if the technical as well as commercial challenges can be met, it is - despite it is low data rate - the ideal solution for the task at hand. Even more, it has the potential to revolutionize the home automation market as well.

The “wireless-plug” systems studied herein have the advantage that they can be ordered and used today. But looking at their features, the level of integration, the reliability and also the business model, we see them as semi-professional solutions that may close a market niche for technically affine, sensitized and interested home users until “dS-like” systems or even advanced smart metering systems enter the market, or these systems are introduced into the lives of customers by electricity suppliers.

Here it seems important to mention that this report did not consider “conventional” smart meters which are rolled out in many European countries at the moment which allow accurately measuring, collecting and communicating of the overall electrical consumption or even water and gas usage in private households. Although reports [1] have shown that the motivation to save energy is high and more detailed the consumption can be presented, it is yet unclear whether the additional effort needed to measure at an individual consumer level is worth the benefit achieved through such systems. What’s more, sophisticated algorithms and methods are able to make educated guesses about individual consumers looking at the characteristics of the overall consumption curve or analysing signals on the power line when certain loads are switched on and off (load fingerprinting). What they cannot do is switch an individual load, and for this one needs a client device near the load that enables/disables it. Considering the high potential and commercial impact of load control applications, this feature should not be underestimated.

Of course, commercial building automation systems are able to do such tasks. But although the final price of a complete dS system is yet unclear, we think that the commercial automation solutions available on the market today cannot compete against it in the low-cost home automation segment.

The question is, if - for whatever reason - dS will not penetrate the market as expected, is there an equivalent to it? The fact is that only a low-cost, low-power system which is reliable and easy to install, integrate and use will be successful in the long run; and in mass market the high volume of units sold and a high integration level will bring down its price. There is no such known system, and such a specialized system is hard to equal, but how could an alternative be constructed built-up from technologies available today? The following table tries to give some general recommendations and hints from experience and knowledge gained in this field of how this system might look like if state-of-the-art commercial parts are used. Since the solution does not involve the development of a single chip solution, it could not be as small and cheap as dS could be, but it can be built today and is small enough to fit into a device, plug, or electrical outlet.

Topic	Suggested solution
Integration	Client component that can be directly built into electrical outlets, plugs or devices.
Communication (PHY)	Clients: IEEE802.15.4-mesh network. If a reliable narrowband PLC technology comes out, we see a seamless combination of wireless and PLC technologies as a good solution for low-power, low-cost in home networks in general. The server has a WiFi interface to be accessed over a PC.
Communication (Protocols)	There is a strong trend towards using IETF protocols also for these types of networks (IP, 6LoWPAN, ROLL,...).
Embedding	Small embedded server for data collection, storage and control tasks (home server). Such a server could also be integrated in a "picture frame" type of device which also serves as energy display (MEGA approach [1]) or within a wireless router (such as Vera).
Measurement	Accurate metering chips have become quite cheap when ordered in large quantities (e.g. a 3-phase measurement IC is CHF 4.40). The straight-forward solution is to take such a chip accompanied by a shunt and integrate it into the client. However, a central measurement system (with data analysis capability) would be preferable, though feasibility of such a system is not yet proven. Requirements: The accuracy of the measurement system should lie at around 1%, it should cope with inductive/capacitive loads and be able with loads in stand-by mode (~2W).
Load Switching	Solid-state relay (e.g. Sharp, 16A, CHF 3.4).
Installation	Client components: Integrated in outlets, plugs, or embedded in new devices. For retrofitting, the electrical outlets would have to be replaced by a technician. Server component: Similar to installation of an embedded device; with user confirmation required for newly discovered devices. Connection clients/server: IP based Plug and Play protocols that like DPWS.
Home automation and control	Performed through the embedded server, similar to dS. Dimmers and light switches can be configured to address particular clients by themselves or through the embedded server; and have the potential to be powered by energy harvesting.
Interfaces and extensibility	Server: WiFi (optional LAN port) to the outside world Clients: IPv6 over IEEE802.15.4 and/or PLC Standard protocols and API's based on open standards

	Server software based on Linux, but not necessarily open source
Data collection and processing	Data collected and processed mainly on the embedded server, with PC software as option for backups and extended analysis.
Security and safety	Standard encryption, authentication and error detection provided by IEEE802.15.4, WiFi and the Internet suite of protocols.

Table 14: Semi-integrated alternative made of standard components available today

In conclusion, we share some thoughts and trends that we have observed during this work:

Research and development in the field is very active at the moment. Many new innovations are planned for release through 2011. In the pursuit for more energy efficiency, many leading companies and utilities are looking for solutions in the household sector. dS has taken up the idea quite early, followed by years of development (patent filing date 2005). Systems that begin from scratch can take years to develop, verify, certify, and deploy. As far as we know, there is no existing or near future alternative around now, that is publically known. With today's knowledge and technologies, and if certain requirements can be relaxed (no "single chip"), the development time can be considerably shortened.

The trend for open systems or at least systems that base on open protocols and standards is still continuing; the observation is that open systems spur innovation and improvement of the system through contribution where technically affine customers are involved. Automation, as control circuitry becomes less expensive, will continue to be embedded into more products. We believe that "energy aware" devices, sockets, plugs - integrating a measurement and control part - are the future. But such a system can simply not be provided by a single source. Industrial partners from many different domains have to continue to work closely together to achieve this goal.

References

- [1] M. Fercu, A. Egli, J. Gallati, R. Kistler: **BFE MEGA Recherche und Konzeptstudie, Hochschule Luzern**, V0.72
- [2] **iHomeLab** - Denkfabrik und Forschungslabor für Intelligentes Wohnen – Hochschule Luzern, [Online] <http://www.iHomeLab>
- [3] **digitalSTROM** - [Online] <http://www.digitalSTROM.org>
- [4] **YelloStrom** – [Online] <http://www.yellostrom.de>
- [5] **Cornell Powerbox** - [Online] http://instruct1.cit.cornell.edu/courses/ee476/FinalProjects/s2008/cj72_xg37/cj72_xg37/index.html
- [6] X. Jiang, S. Dawson-Haggerty, P. Dutta, and D. Culler: **Design and Implementation of a High-Fidelity AC Metering Network**
- [7] **Berkeley ACme** - [Online] <http://www.eecs.berkeley.edu/Research/Projects/Data/105694.html>
- [8] **WEBnergie** - [Online] <http://www.geroco.com>
- [9] **Plugwise** - [Online] <http://www.plugwise.com>
- [10] **Plogg** - [Online] <http://www.plogg.co.uk>
- [11] **Tendril Volt** - [Online] <http://www.tendrilinc.com/consumers/products/volt/>
- [12] **EnergyHub** - [Online] <http://www.energyhub.net>
- [13] **TalkingPLUG** - [Online] <http://www.zerofootprint.net/press/categories/category/TALKINGplug/>
- [14] **eMonitor** - [Online] <http://www.powerhousedynamics.com/>
- [15] **4Home** - [Online] <http://www.4home.com/solution-set/energy-management-2>
- [16] **DomotiGa** - [Online] <http://www.domotiga.nl>
- [17] **BWired Plugwise Page** - [Online] <http://www.bwired.nl/plugwise.asp>