Survey on Energy Efficiency in Office and Residential Computing Environments

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Abstract

Energy efficiency of computing equipment in office and residential environments gets more and more important, with respect to the world-wide desire to reduce CO_2 emissions and the increasing cost of energy. While hardware itself gets cheaper, the cost of energy begins to dominate the total cost of ownership of a product. This paper gives an overview on energy saving methods that are applied today, with a special focus on office and residential environments. Currently used methods are classified into three categories: (1) autonomous management of devices, (2) coordinated management of devices, and (3) coordinated management of services. Various implementations of these methods in office and residential environments are described and compared to each other. The comparison illustrates possible directions of future research in the area of energy efficiency.

Keywords: energy efficiency, office environments, residential environments.

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1 Introduction

Energy-efficient Information and Communication Technology (ICT) is fostered by labels such as the U.S. Energy Star [8] or the European TCO Certification [16, 22, 35]. Furthermore, regulations as the European Energy related Products Directive [4] and the European Codes of Conduct [36] rate IT equipment according to their environmental impact.

The strict separation between the often used terms energy efficiency for ICT (making ICT energy efficient) and ICT for energy efficiency (using ICT to achieve energy efficiency) [52] is vanishing in the area of residential and office environments. More and more non-IT equipment joins the network (i.e., gets an IP-address and becomes manageable [42, 44]), as the Internet of Things embraces more and more devices. This opens up the opportunity to save energy in classical non-IT equipment as well as in IT equipment by using the same management mechanisms. The U.S. Energy Information Agency [17] reports, that home electronics including IT equipment as PCs and entertainment TV sets account for 7% of the electricity consumed by U.S. households. Moreover, the European Eco-Design Directive [4] shows in recent studies [31] that IT equipment as PCs, peripherals, printers or phones exhibits in total consumes more energy than data centers. The carbon footprint that is related to usage and directly corresponds to the energy consumption is shown to be 259 Mt CO_2 in 2002 and predicted to be 640 Mt CO_2 in 2020 (60 and 59% share of the global ICT footprint). For example the Telecom device's global footprint was 18 Mt CO_2 in 2002 and is expected to increase almost threefold to 51 Mt CO_2 by 2020 driven mainly by rises in the use of broadband modems/routers and IPTV boxes.

Obviously the energy-saving potential in residential and office computing environments is huge, but due to their distributed nature and heterogeneous device landscape hard to exploit. This paper analyses energy-saving methods that are available for IT equipment. It classifies current work into three main categories of energy-saving methods: (1) Autonomous management of devices enables the reduction of energy consumption locally at a single device (e.g., by built-in energy-efficiency features). (2) Coordinated management of devices enables the optimization of the energy consumption of a group of devices that actively exchange energy-related information. (3) Coordinated management of services enables the replacement, delegation, and consolidation of services and aims at optimizing the energy consumption of a service or a group of services. In addition, this paper explores and compares implementations of energy-saving methods of each category in the context of office and residential environments.

The remainder of this paper is structured as follows: Section 2 categorizes current energy-saving methods. Sections 3 and 4 analyse the application of these methods in office and residential environments. Section 5 provides a comparison of energy-saving methods concerning their use in both environments, and Section 6 concludes this paper.

2 Energy-Saving Methods

This section identifies three disjunctive categories of energy-saving methods that reduce the energy consumption of devices. For each category several examples are described.

2.1 Autonomous Management of Devices

Autonomous management of devices covers energy management methods that reduce the energy consumption of a device without coordination with other devices or the user. Instead, the device exploits its built-in energy efficiency features autonomously. *Dynamic external condition adaption* monitors conditions that are caused externally (as CPU-workloads, CPU-temperatures, or user-interaction) and manages parts of a device accordingly.

The goal of the adaption is to dynamically adapt the managed device to its environment in a way that the energy consumption of the device is reduced. It is important to see that this happens without a conscious interaction of the user. Examples of dynamic external condition adaption are:

- A monitor is dimmed in reaction to low light conditions.
- A fan is slowed down if the CPU is below a certain temperature.
- Hardware parts are incrementally turned off due to sensing a lack of user-machine interaction (e.g., display or disk).

2.2 Coordinated Management of Devices

In contrast to the autonomous management of devices, the coordinated management of devices addresses the cooperation between devices.

Automatic coordination reduces the energy consumption of a set of devices by exchanging energy-related information that eases up energy management decisions. The purpose is to reduce the energy consumption of a whole set of devices instead of locally optimizing the energy consumption for each single device. Inter-device coordination can be achieved in a centralized or decentralized way. In a centralized coordination approach, a centralized entity either polls information from the managed devices or the managed devices inform the managing entity periodically or at the occurrence of an energy-relevant event. Based on the gathered information and policies, the central entity instructs devices to apply power saving methods. Coordination can also be achieved in a decentralized way, where energy-related information is exchanged, but decisions are made based on the local view of each device. *User-based coordination* is triggered by implicit or explicit interaction between user and device. On one hand, the device may push information to the user, e.g., a visualization of the current energy consumption of the device. On the other hand, the user is able to directly control the device, e.g., by sending the device to hibernation mode actively. Besides the energy savings that are directly achieved by this approach, there are additional psychological effects that foster the energy-efficient behaviour of a user: Immediate feedback on the effects of his actions motivates energy-efficient behaviour. Also competitive situations between users may be established, further motivating users to behave energy efficiently.

Examples of coordinated management of devices are:

- Cisco's EnergyWise [33] (see Section 3.2) represents a centralized management approach. A centralized server powers up/down groups devices, e.g., according to working/non-working times.
- The Energy Efficient Ethernet (EEE) standard (IEEE 802.3az [5]) is an example of decentralized management approach. During times without demand of data transmission, devices negotiate a low-power idle mode.
- Products as Kill-A-Watt [45] or Watts Up [19] (see Section 3.2) are products that support user-based coordination. They adapt their energy consumption to user behaviour and visualize consumed energy.
- Projects that have been performed in residential environments [43, 51] have shown that real-time feedback on power consumption leads to a reduction of energy consumption by up to 10%.

2.3 Coordinated Management of Services

Although services (e.g., print-servers, Open VPN servers, peer-to-peer clients, or user desktops) do not consume energy directly, they utilise devices and cause energy consumption indirectly. This category of methods reduces the energy consumption of services, by replacing, delegating, or consolidating them.

Service replacement is an approach for energy saving were services are replaced by more energy-efficient services that provide the same (or similar) functionality. Although the energy-saving effect of service replacement can be large, the overall impact on energy consumption is difficult to assess. It may even happen that the overall energy consumption increases, if the so-called rebound effect occurs. This effect describes the situation that a new energy efficient service is so attractive to users that a high demand is created which partially or fully compensates for the energy-saving effect of the replacement. *Service delegation* allows the transfer of a service from one device to another, e.g., from a non-energy efficient to an energy-efficient device or to an always-on device (e.g., a router). The main goal of service delegation is to allow under-utilised devices to delegate their services to other devices and change to an energy-saving mode. *Service consolidation* is based on the ability of devices to process more than a single service at the same time. The goal of service consolidation is to reorganise the service to device mapping within a group of devices in order to minimise the number of utilised devices. This means that the utilisation of some devices is increased while other devices are relieved from their duties. Unutilised devices are hibernated to save energy. Service consolidation can be done statically or dynamically. If it is done statically, a set of devices is determined that processes all required services. If the external circumstances change, the allocation of the services is not dynamically adapted. Dynamic service consolidation, in contrast, allows for the relocating of devices when external circumstances change, e.g., the loads of services change, or a device fails. Examples of service replacement, delegation, and consolidation are:

- Terminal servers [13,14,20] and virtual desktop infrastructures [3,18,21] (see Section 3.3) replace user desktops in office environments. Instead the desktops are consolidated on servers within the data centre.
- Virtual private network server services can be delegated to the home gateway (router) in residential environments.
- Cloud computing achieves energy efficiency [28, 37, 48] (see Section 4.3) by consolidating user services (e.g., storage services) within data centres. Cloud providers achieve a high utilisation of hardware and customers can dynamically allocate and release resources in the cloud.

3 Office Environments

Office computing environments consist, e.g., of office hosts, network, peripheral devices as monitors, printers, scanners, and IP-phones. Within office environments, especially office hosts contribute significantly to the IT related energy consumption. On one hand, there is a high number of such hosts because usually each employee typically has his own host. On the other hand, office hosts are often turned on 24/7. Webber et al. [50] have analyzed sixteen office sites in the U.S. and reported that 64% of all investigated office hosts were running during the nights. Although such hosts are mostly idle (CPU usage of 0%) during the time they are turned on, it is important to see that they still consume a considerable amount of energy. Measurements that have been performed at the University of Sheffield [32] show that typical office hosts which are idle still consume 49 to 78% of the energy that they need when they are intensely used, leading to an immense waste of energy.

3.1 Autonomous Management of Devices

Current office computing equipment often has the ability of saving energy by falling into low-power states if it remains unused for a critical period of time. Hosts, monitors, or printers are dynamically hibernated to save energy. The low-power states of office hosts can be configured by the user and kick in when a host is idle for a critical time period. The Advanced Configuration and Power Interface (ACPI) specification [38] defines four different power states that an ACPI-compliant computer system (e.g., an office host) can be in. These states range from G0-Working to G3-Mechanical-Off. The states G1 and G2 are subdivided into further sub-states that describe which components are switched off in the particular state. Separate power states (D0-D3 for sub-devices and C0-C3 for CPUs) are defined, similar to the global power states [7, 34, 38]. However, as a matter of fact, many devices that are low-power capable do not successfully enter these states. Low-power modes are subject to the complex combined effects of hardware, operating systems, drivers, applications – and after all – the user-based power management configuration. Webber et al. [50] report that in the investigated offices only 4% of all hosts actually have switched to low-power modes during the night.

3.2 Coordinated Management of Devices

In office environments power management solutions are able to optimise the energy consumption of hosts that remain turned on while their users are absent. Examples of this approach are eiPowerSaver [6], Adaptiva Companion [2], FaronicsCore [9], KBOX [11], or LANrev [1]. office-wide power management policies are applied in such approaches. Office hosts are forced to adopt power management configurations, independent of user settings. Therefore, idle hosts can be set to a low-power state or be powered off to save energy. Additionally, often mechanisms are provided by such approaches to wake up hosts if necessary (e.g., based on Wake-on-LAN technology). This way, inactive hosts can be accessed for administrative jobs (e.g., backups that happen during the night) and for remote usage. Cisco's EnergyWise controls office equipment that is powered by Power over Ethernet (PoE). It can be used to power down IP-phones during nights and to power them up again in the mornings. Additionally, EnergyWise can be used to apply energy management to hosts and to report energy savings within the office.

There are also user-based coordination methods available in offices: The approach of Greentrac [12] is setting its focus on the user's energy awareness. A user is periodically informed about the energy consumption of the devices he is using. If the user is aware of the energy consumption he causes, he is able to change his behaviour in order to save energy. The Greentrac-approach uses incentives to motivate the employees to implement energy-saving measures.

3.3 Coordinated Management of Services

A typical example of service replacement and consolidation within office environments, is the replacement of energy-consuming office hosts by highly energy-efficient *thin clients* [49]. *Terminal-server* approaches, e.g., move user desktops to centralized terminal servers that are able to serve multiple users simultaneously (consolidation). Terminal-server solutions are based on multi-user concepts where several users are able to log-on to a single OS that is provided by the terminal server. OS, applications, and user data are stored in the data centre and can be remotely accessed by thin clients. Common terminal server software products are Citrix XenApp [20], Microsoft Windows Server 2008 [14], or the Linux Terminal Server Project [13].

In the *Virtual Desktop Infrastructure (VDI)* approach each user gets his own Virtual Machine (VM). Similar to terminal servers, the VMs are stored within the data centre and can be accessed remotely by energy-efficient thin clients or any host with remote desktop software. In contrast to the terminal server approach, the VDI approach has the advantage that each user can utilise his preferred OS and individual applications (not all standard applications are able to run on terminal servers) and new virtualised desktops can be

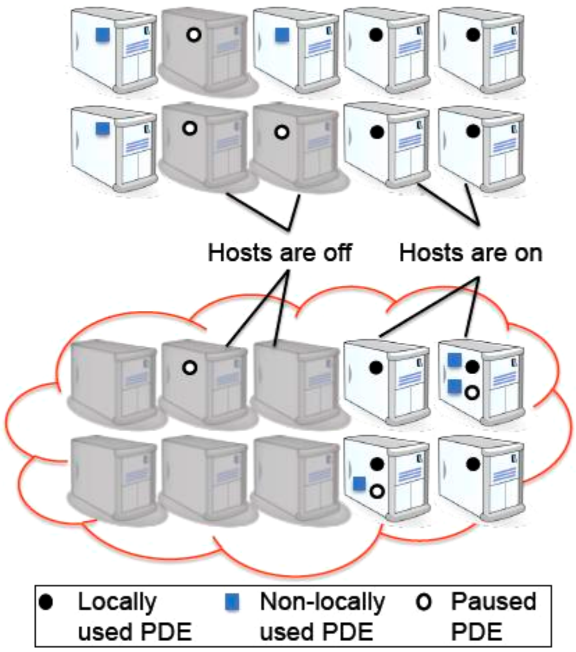

Figure 1 Common and virtualised office.

easily deployed. Furthermore, the virtualised desktops are strictly isolated from each other, while being managed within the data centre. However, it is important to see that the provision desktop environments within VMs is demanding: All of the VMs need a sufficient amount of CPU cycles, RAM, disc I/O, and other hardware resources to operate. Therefore, the number of VMs that can be provided by a single server is rather limited. VDI products are, e.g., VMWare View [3], Citrix XenDesktop [21], or Parallels Virtual Desktop Infrastructure [18].

In [24–26, 30], a virtualised office environment is suggested that achieves a consolidation of services within office environments, independent of data centre equipment. Office hosts are virtualised and virtual desktops are consolidated dynamically on office hosts. Whereas terminal server and VDI solutions impose changes to the office environment (thin clients replace full featured office hosts), the virtualised office environment utilises available office hosts. Terminal servers and VDIs, instead, move office services into the data centre, which has two main disadvantages: First, additional hardware needs to be purchased and managed, second, the additional data centre hardware consumes energy itself. Data centre equipment typically consumes more energy than desktop hosts [41], due to high-performance parts, parts that provide redundancy, and, especially, the cooling that needs to be applied within the data centre.

In Figure 1 the transition from an ordinary to a virtualised office environment is illustrated. It can be observed in the upper part of the figure that in the ordinary office environment the Personal Desktop Environments (PDEs) and the hosts are interdependent. Seven hosts are turned on together with seven PDEs and three hosts (with PDEs) are turned off. The situation is different in the virtualised office environment shown in the lower part of the figure. Although the number of currently running PDEs is the same as before, only four hosts are actually turned on. It can be observed, e.g., that the upper right host is providing three PDEs to users simultaneously.

Possible savings of about 50% of energy are reported with this approach [24]. In comparison to VDI solutions which are able to save energy for office environments with more than 25 hosts [40], the virtualised office environments saves already energy in offices with only 4 hosts.

4 Residential Environments

More and more end-users have residential computing networks that consist of desktops, laptops, game pads, or home theater PCs. Such devices provide all kind of applications, including client, server, or peer-to-peer. Typically, residential networks have a gateway (residential gateway) to the Internet, e.g., a Digital Subscriber Line (DSL) router.

Although office and residential environments seem to be similar on a first glance, there are some major differences: in the office environment rather homogeneous office hosts are interconnected via Fast/Gigabit Ethernet and administered by a professional administrator. In residential environments, highly heterogeneous hosts are usually connected to the Internet via DSL-connections, which typically have asynchronous up/download capacities and are administered by individual users. The access technology can be both, wired as well as wireless. In residential environments, the users may be children or adults with certain rights and restrictions in the home network. This prevents the use of uniform security policies.

4.1 Autonomous Management of Devices

Similar to hardware of office environments also residential equipment performs a dynamic adaption to external conditions. Home IT-equipment (as laptops or printers) is able to sense a lack of user interaction in order to turn into a hibernation mode. The residential gateway is a device that is constantly turned on and typically provides a wide range of autonomous power management features. Even in the case of no user interaction, a large number of functions have to remain active to guarantee good user experience and to fulfill industry standards:

- A DSL-IP connection is required to receive VoIP calls. To transmit the IP stream the physical layer has to be kept active.
- The WLAN base station has to transmit beacon signals in order to perform the association of new mobile devices to the WLAN network and to maintain the wireless link to previously associated devices.
- Ethernet link detection has to be active and attached devices have to be managed when requesting a new link.
- For the DECT/CatIQ cordless telephony interface the incoming call detection has to be assured for all interfaces.
- The attachment of new devices to USB needs to be detected.

The list indicates some minimum active functions which have to be maintained during autonomous management. In addition, other services may be required to like for example FTP server functionality, multimedia server or home automation functions. If the user actively decides not to use WLAN during night time,e.g, it can be turned off by using an autonomous timer based management that is configurable by the user.

4.2 Coordinated Management of Devices

Home automation, e.g., provides a coordinated management of non-IT devices in the residential environment. Standards as G.hn [23] allow the connection of devices over any wire (power line, coax cable, phone line) or Wi-fi wireless connection.

Studies of the U.S. Energy Information Agency [17] show that major energy consumption in households stems from classical non-IT equipment. Therefore home automation opens a promising new opportunity for power saving by including additional information for example from sensor networks to energy management decisions.

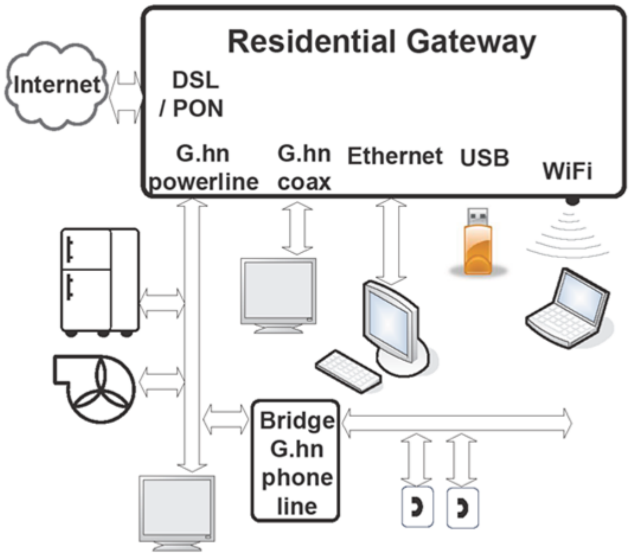

Figure 2 Home automation network.

An example of a home automation network architecture is illustrated in Figure 2, where a residential gateway is connecting multiple physical media forming together a heterogeneous network reaching virtually every controllable device. A DSL or Passive Optical Network (PON) interface offers Wide Area Network (WAN) services using broadband residential network. G.hn standard ports are used for coaxial cable and powerline communication. Phones and phone-line devices are included via an inter-domain bridge. Ethernet LAN and USB devices are also covered. Residential gateways allow the processing of automation applications inside the gateway independent from running PCs, which substantially saves power. Residential gateways are typically "always on" devices and form a natural central point for home networking.

Also user-based coordination is achieved within the residential environment. Emerging technologies as, e.g., smart metering approaches raise the user's energy consumption awareness. Energy consumption can be monitored locally and remotely [47]. This is important to keep users aware about their energy behaviour. Having real-time feedback on current energy consumption allows the user to link his actions to an increase of energy consumption. Taherian et al. [46], e.g., describe an energy monitoring system for resid-

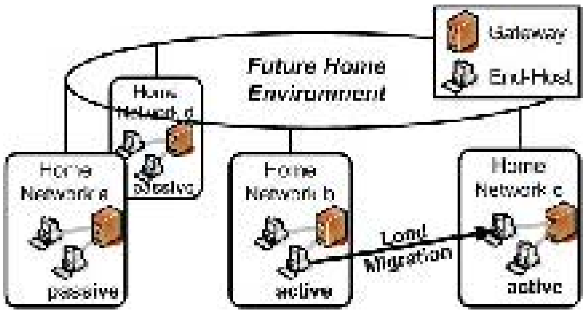

Figure 3 FHE architecture.

ential and office environments that supports continuous real-time feedback on energy consumption.

4.3 Coordinated Management of Services

Also service delegation and consolidation is achieved in residential environments. In this field the residential gateway plays a key role. Residential gateways mediate access to the Internet, run services on the user's behalf, and control IT and non-IT equipment. Furthermore, residential gateways are able to support the coordinated management of services and are able to provide services themselves energy efficiently: Residential gateways can provide access to peripheral devices as USB-Disks, printers, Network Attached Storage (NAS), multiport routing, switching and encryption, VoIP telephony functions (e.g., DECT/CatlQ or VoIP FXS/FXO H.323), or they can run P2P software as BitTorrent or eDonkey.

Based on such residential gateways, Berl and co-authors [27–29, 39] describe a Future Home Environment (FHE) that enables an energy-efficient consolidation of services in home networks. It suggests the sharing of home network resources with users of other home networks, similar to Grid computing approaches. Load is shifted to a small number of computers, in order to relieve others. Unloaded computers are hibernated or turned off. A home network is called active if it contains at least one computer which is turned on and can share resources. In a passive home network only the gateway is on-line and other hardware is hibernated or turned off.

The FHE architecture is illustrated in Figure 3. In this example four home networks are interconnected by the FHE overlay, two active and two passive homes. In the figure load is migrated from an end-host in the active home network (b) to an end-host in the active home network (c). The end-host in home network (b) can be hibernated or turned off after the migration process. If no further computer is turned on in home network (b), it can change its status to passive.

5 Comparison

Most of the energy-saving methods that have been described in Section 2 are applied in office and residential computing environments (see Sections 3 and 4). Whereas the autonomous management of devices is implemented similarly in office and residential environments (hibernation of unused devices), the coordinated management of devices is implemented diversely in the two environments. On the one hand, office-wide power management approaches and the controlling of PoE devices is applied in office environments. Such mechanisms can be easily applied, due to the rather homogeneous office computing environment and similar usage patters of office users, which eases up the energy management: Sets of devices can be hibernated, e.g., according to time-based energy-saving policies (working/non working times). Multipurpose devices of residential networks, on the other hand, are rather heterogeneous and the behaviour of the users is less predictable. The management of the devices needs to be done in a context-aware way, where the behaviour of the users is monitored in order to take management decisions. Also waking up devices is often easier in office environments as Wake-on-LAN can be applied to devices that are connected to wired networks. In residential environments many devices are attached wireless to the home gateway which makes it hard to wake them up remotely. Instead, home automation systems are applied that mainly adapt energy consumption of non-IT devices to the behaviour of persons in a household.

The user-device interaction for energy-saving requires users sufficiently trained and with awareness of energy consumption. The typical residential-user will need a simple and easy to use interface that provides direct feedback on energy consumption. Independent of residential or office environment the general consciousness of energy saving is key to motivate user to take action.

The application of coordinated management of services, however, is unbalanced between office and residential computing environments: Service delegation is typically applied in residential environments. Home Gateways take over services as, e.g., printing servers, network storage servers, or servers for DECT phones and needs to be further exploited in office environments. Together with the novel approach of the Virtualized Office Environment (as described in Section 3.3) the energy consumption of offices can be reduced, especially if no data centre infrastructure is available. Whereas service replacement and consolidation has already been applied widely in the area of office environments (in terms of virtual desktop infrastructures and terminal servers), it is not yet sufficiently exploited in residential environments. Novel approaches, as the Future Home Environment (see Section 4.3), provide a high potential of energy saving in this area. Also the paradigm of cloud computing can be further exploited: Instead of thin-clients, users of residential networks are able to use energy-efficient equipment as smart-phones, tablets, or netbooks to access cloud-based services. Gaming PCs, desktops, or home theater PCs may not be needed anymore in future residential network scenarios. There are already some approaches available, as e.g. OnLive [15] or GAIKAI [10], where demanding 3D games can be played within the cloud.

6 Conclusion

This paper has reviewed the state of the art of available energy-saving methods, especially concerning office and residential environments. Currently applied methods have been categorized into three classes: (1) The autonomous management of devices allow devices to reduce their energy consumption individually, without active cooperation of other devices or humans. (2) Coordinated management of devices covers automatic management as well as user interaction. In contrast to the first category, such strategies save energy through cooperation, using energy-relevant signalling to exchange information. Groups of devices are managed cooperatively (or are managing themselves) to achieve the common goal of a reduced energy consumption. Finally, (3) the coordinated management of services performs the replacement, delegation, and consolidation of services in a cooperative way to reduce the overall energy consumption.

Although all of the mentioned categories are applied within office environments as well as in residential environments, their application is unbalanced. Especially, the coordinated management of services provides a high potential of energy savings that can be exploited by future developments.

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