Energy performance assessment of HVAC systems by inspection and monitoring

Marco Masoero, Chiara Silvi and Jacopo Toniolo

Dipartimento di Energetica - Politecnico di Torino, Italy

Corresponding email: marco.masoero@polito.it

SUMMARY

The paper discusses the collection and processing of energy performance data as part of the inspection of HVAC systems, aimed at identifying technically feasible and cost-effective Energy Conservation Opportunities (ECO), as required by EPBD. Case studies developed by the HARMONAC project have shown that low-cost or no-cost ECO's - mostly related to system operation and management - can be identified with an effective system monitoring. Building Management Systems (BMS) may be a powerful tool for this task, provided their HW and SW architecture is designed with adequate attention to energy monitoring. Dedicated instrumentation – such as electricity meters and temperature loggers – may also be employed as an alternative / integration to BMS monitoring. The paper also discusses the application of data analysis tools – such as "carpet plots" and "energy signatures" – to the identification of component malfunctioning, control problems, inadequate maintenance, or system schedule optimization, and to the evaluation of achieved energy savings.

INTRODUCTION

The Intelligent Energy Europe (IEE) funded HARMONAC project [1], due to completion in August 2010, is developing a set of inspection and energy audit procedures suitable for fulfilling the requirements of article 9 of EPBD [2], which establishes the mandatory inspection of HVAC systems of rated output above 12 kW. The inspection and audit procedures proposed by HARMONAC are now being tested by the project partners over a wide range of field trials and case studies throughout Europe.

One of the key points of the inspection procedure is the availability of reliable energy performance data of the main components of the HVAC system. This task is usually easy for heating only systems, such as gas boilers coupled to hydronic heating plants, but much more complex for systems delivering both heating and cooling. In the latter case, in fact, most system equipment (e.g., water chillers, cooling towers, AHU fans, chilled / hot water pumps, fan coils, etc.) are electrically-driven, but the electricity consumption is seldom measured in a disaggregated way. Normally, the only available electrical consumption data are those measured at the main incomer, and therefore also include the contribution of lighting and appliances. One of the main problems that have been addressed by the HARMONAC team has therefore been the definition of energy data collection protocols, suitable for an effective inspection and energy auditing process of existing HVAC systems.

This paper presents the main findings obtained by the authors through the energy and performance monitoring of a set of tertiary buildings in Northern Italy, which include laboratories, hospitals, and office buildings of different ages. HVAC systems that have been investigated include air, water, and air-water units (with fan coils, chilled beams), air cooled chillers, reversible heat pump systems of various characteristics (variable refrigeration flow air-to-air HP, closed-loop ground source HP, open loop water to water HP). Specifically, this paper presents a subset of case studies, addressing the following issues:

- How to obtain reliable and sufficiently disaggregated energy consumption data using the existing BMS, and which SW and HW features are required for this purpose.
- Further information that can be obtained by installing dedicated instrumentation.
- Approaches to energy data processing - e.g. correlation of primary energy consumption with climatic conditions and occupancy characteristics - and determination of suitable energy performance indexes.
- Identification and assessment of cost-effective Energy Conservation Opportunities (ECO's) [3], which have been implemented in practice and checked in actual case studies: examples include modified operation schedules, improved control strategies, maintenance or improvement actions on specific HVAC components.

Results indicate that primary energy savings typically in the 5%-25% range, and up to 60% in peculiar circumstances, may be reached by applying low-cost (or no-cost) measures identified by analysing data that are acquired with dedicated instrumentation, or are provided by a BMS that has been properly designed, installed and commissioned for energy monitoring.

DATA COLLECTION AND PROCESSING

Hardware and software requirements of BMS

Most tertiary buildings of new construction, or undergoing radical refurbishing, are now being equipped with sophisticated and powerful computer-based Building Management Systems (BMS), which monitor and control mechanical and electrical equipment such as lighting, power supply, fire prevention, security, and HVAC [4]. BMS can effectively perform energy metering (fuel consumption, electrical energy input to specific components, delivered energy to fluid networks), provided the energy metering functions are clearly indicated among the design specifications of the BMS in terms of installed instrumentation (electricity meters, temperature sensors, fluid flow meters, etc.), and SW characteristics. Our experience indicates, on the contrary, that adding such capability to an existing BMS implies very high costs and technical problems that are sometimes impossible to overcome.

The experience gained in using existing BMS for HVAC energy monitoring has yielded several hints which may eventually lead to a complete specification. The following is a non-exhaustive list of recommendations to the designers and installers:

- Electric meter characteristics (type of data collected, accuracy, data storage) and number (e.g. separate chillers + cooling tower, pumps, AHU).
- Thermal energy meters: specifications for hot water and chilled water flow rate and temperature measurements.
- Environmental data measurements: indoor and outdoor air temperature and RH.
- Time coding: the data acquisition time interval should be specified by the user, typically in the range from 15 minutes up to 1 hr, depending on the type of data; the time sequence of collected data should never be interrupted, which means that, if for any reason the data are not collected at a given time, a conventional figure should be recorded. It should be clearly stated how summer daylight saving time is managed by the system.
- Data format: the correspondence between data and physical quantities should be clearly specified with alphanumeric codes that make the identification easy to the inspector.

Data collection with dedicated instrumentation

As an alternative or integration to BMS monitoring, specific data may be collected with dedicated instrumentation. Ambient temperature and relative humidity (RH) data are easily obtained with stand-alone, battery powered loggers. Status loggers should be used to monitor, at relatively low cost, the operation schedule of small fixed power appliances, such as constant speed electric motors of HVAC equipment (typically, constant flow fans and water pumps, fan coils, etc.). The logger simply logs the on/off status of the component by a magnetic field sensor or a single current transformer clamp.

More relevant electrical users should be monitored with energy meters that may be installed on the electric board. In recent plants, the electric meter may be already present in the board, in which case it may be sufficient to connect the meter to a suitable data logger. The most sophisticated measurement units are the so-called "power / energy analyzers", which can provide a complete set of data including active and reactive power, power factor, and the corresponding energy values over a specified integration interval. Power quality analyzers may also provide information on the waveform (e.g. the total harmonic distortion). A summary of the instrumentation characteristics is given in Table 1.

Table 1. Metering instruments utilized

Instrument	Typical values logged	Acquisition time	Memory	Cost (€)
Electrical power meter	kW, kWh, VAh, PF	15 minute	1 year	300-1000
T/RH logger (stand-alone)	°C, RH (%)	1 hour	6 months	120-250
Status logger (ON/OFF)	On/Off status	1 second	8000 COV(*)	100
(*) COV = Change of value				

Analysis of energy performance data

As discussed above, the monitoring process should typically yield the disaggregated values of primary (electric) energy consumption of the main system components. These values are supplemented with a suitable set of environmental and occupancy data, recorded over the same time scale, that are likely to influence the system energy demand. The level of disaggregation of the acquired data varies significantly from case to case: in some buildings, the total electrical consumption was only available (i.e. the typical "billing data" provided by the electric utilities), while in other cases the BMS allowed the separate measurement of the energy input to the main HVAC sub-systems (e.g., dedicated meters for: chillers and cooling towers; water circulation pumps; and Air Handling Units). For some HVAC systems, dedicated equipment was installed for a detailed analysis of "critical" components, such as the AHU of the operating block of a hospital.

The availability of such data sets makes it possible to perform an energy analysis, based on the so-called "data-driven" modeling approach. According to ASHRAE [5], data-driven methods for building / HVAC energy analysis may be classified into three broad categories (Black-Box, Calibrated Simulation, or Gray Box), depending on the type of available data and goals of the analysis. Furthermore, the mathematical approach may vary depending on the basic assumptions, such as steady-state vs. dynamic modeling, or single-variate vs. multivariate regression, etc. In this research, a steady-state, single-variate approach has been applied, considering the daily (or weekly) mean outdoor temperature as the independent variable, and the corresponding daily (or weekly) primary energy consumption of the specific equipment (or system) under investigation. The reason for this choice is that outdoor temperature is the most readily available climatic variable for the inspector, and is also likely to have the main influence on HVAC primary energy consumption. This is a crucial aspect of the inspection process: to be able to get the maximum information from readily available data that may be useful for ECO identification and assessment.

Another useful tool for energy data analysis is the so-called “carpet plot”, which provides a visually grasping representation of temperature or energy consumption trends over long time periods: time of day is indicated on the y-axis, while the day is represented on the x-axis; the value of the variable under observation is encoded, at any time and date, as a colour or shade of gray according to a specified scale [6]. Even if the information provided by the carpet plot is rather qualitative, it allows a meaningful and quick interpretation of the overall system performance in time. This may be particularly useful for identifying anomalous situations, such as excessive energy consumption in non-occupancy periods which may be caused by unwanted equipment operation, or unsatisfactory temperature values due to poor control.

EVALUATION OF ENERGY CONSERVATION OPPORTUNITIES

A sample of four case studies from the HARMONAC project are presented in this paper, which consist of detailed building and system inspection and monitoring (Table 2)

Table 2. Case studies: building and HVAC system characteristics

	Type / location	Area (m^2)	Main HVAC system characteristics
1.	Operating rooms NW Italy	300	15500 m^3/h outdoor air (15 ach) AHU 2 air-cooled chillers, 394 kW total cooling
2.	Office building NW Italy	3500	Air-and-water HVAC (four-pipe active chilled beams) 2 chillers + evaporative tower, 650 kW total cooling
3.	Office building NW Italy (Torino)	9400	Air-to-air reversible VRF heat pump, 600 kW heating, 550 kW cooling. 5 primary air AHU’s
4.	Public building NE Italy	4000	Two-pipe fan coil system, no mechanical ventilation open-loop groundwater-cooled chiller, 330 kW

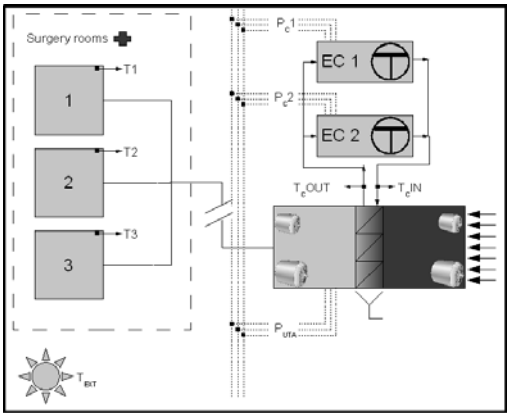
Table 3 summarizes the ECO’s that have been identified and evaluated as part of the four case studies, with an assessment of expected energy savings. All ECO’s belong to the O&M (Operation & Maintenance) category and may therefore be implemented at virtually no-cost.

Table 3. Examples of ECO’s assessed on measured data

	ECO description	Potential savings
1.	Avoid simultaneous heating and cooling	61.5% on winter chiller consumption
2.	Improvement of chiller control	8-15% on annual chiller consumption
3.	Shut off chiller when not required	30% on annual chiller consumption
4.	Shut off VRF system when not required	26.7% on weekly winter VRF consumption
5.	Reducing operation time of chiller	6.2% per hour of daily operation reduction

Case Study 1: Inspection and monitoring of the operating rooms of a general hospital

The experimental setup for the monitoring of the three operating rooms is shown in Figure 1. The graphs in Figure 2, representing the indoor and outdoor temperature values measured over a five week period in November – December, indicate that the HVAC system does not always allow a satisfactory temperature control during surgical activities (i.e. T > 22°C), even with low outdoor temperatures and with the chiller continuously operating at about 25% load. This circumstance can be better appreciated in the carpet plot on the right part of the figure.



EC1: electric chiller no. 1
EC2: electric chiller no. 2
P_c1: active power of EC1
P_c2: active power of EC2
T_cIN: cold water supply temperature
T_cOUT: cold water return temperature
P_{UTA}: AHU fan active power
T1-T3: temperature and RH of surgery rooms 1-3
T_{ext}: outdoor temperature

Figure 1. Operating room HVAC monitoring experimental setup

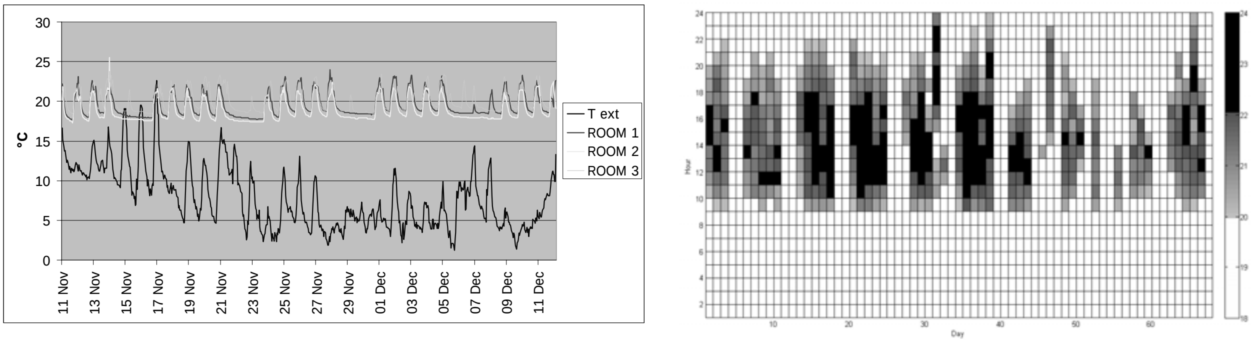


Figure 2. Outdoor and operating room temperatures and carpet plot of room temperature.

Potential energy savings with improved chiller control is assessed with medium term measurements, carried out from December to February. This ECO consists of avoiding simultaneous heating and cooling and shutting off the chiller when outdoor temperature falls below a set level, which, for typical room cooling load values, was assumed 14°C. Over the investigated four-week period (Fig. 3), the chiller electric consumption occurring when the external conditions satisfy the requirement for free cooling is 4’879 kWh, i.e. the 61.5% of the total chiller consumption (7'979 kWh). Extrapolating these figures to the entire year, and taking into account the results of a similar analysis performed in case study n. 2, savings of 8-15% in annual chiller consumption may be expected in comparable climatic conditions.

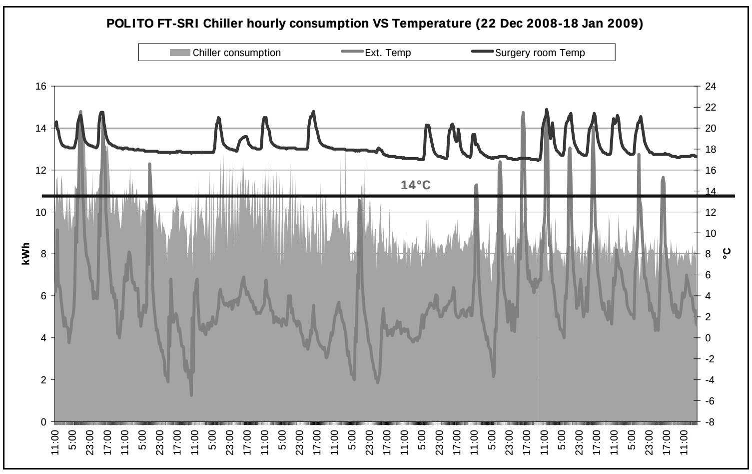


Figure 3. Outdoor / indoor temperature - chiller electric consumption (December – January)

Case study 2: Inspection and monitoring of an office building of recent construction

The preliminary inspection of a newly-constructed office building in NW Italy indicates a relatively high HVAC electric consumption, in spite of state-of-the art system components and building envelope installed, particularly in relation to the climatic conditions of the site. In fact, BMS monitoring data show that about 39% of the total summer electric consumption (51 kWh/m^2) may be attributed to the central cooling plant (20 kWh/m^2), 96% of which due to chillers and cooling tower and 4% to water circulation pumps. These results suggest that significant savings may be achieved by improved chiller control and scheduling.

More detailed analyses performed in the winter season reveal, for example, that simultaneous heating and cooling take place in the AHU under specific circumstances. A detailed monitoring over the January – May period indicates that an improved control strategy, capable of switching off the chiller and exploiting direct free cooling with outdoor air when the outdoor temperature permits, may lead to a 35% reduction in central cooling plant consumption over the investigated five months period.

Another identified ECO is the possibility of turning the cooling plant off at night and during weekends: the BMS data in fact reveal no significant differences in chiller energy consumption between occupied and non-occupied periods (Figure 4). During the monitored January – May period, about 40% of the consumption occurs in the workdays (7:00-18:00) and the remaining 60% during weekends and at night. Spot measurements made during one working day in summer yield opposite percentages: 61% (7:00-18:00) and 39% (rest of day). Extrapolating similar analysis performed in case study n. 3 in which a VRF system was monitored over several seasons with different operating schedules, savings on the order of 30% in annual chiller consumption may be expected in comparable climatic conditions.

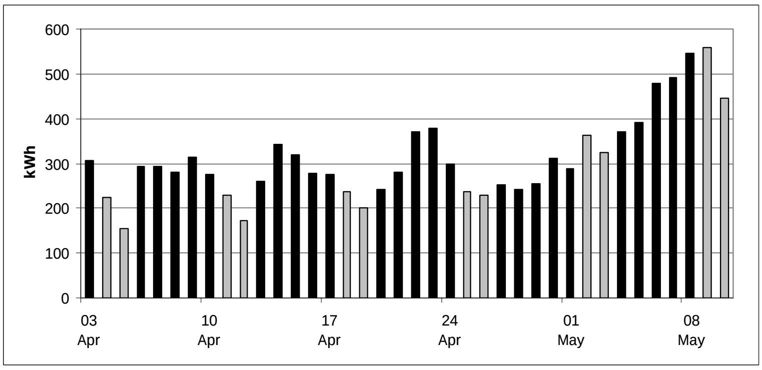


Figure 4. Daily electric consumption of central cooling plant: workdays and weekends

Case study 3: Long-term BMS monitoring of VRF heat pump system

The case study concerns a XVII century building in Torino, which was almost entirely rebuilt after World War II. In 2006, a radical refurbishment of the building services has been completed by the ESCO in charge of the energy service contract and a new modular air-to-air VRF (Variable Refrigerant Flow) reversible heat pump system was installed, consisting of 16 external units and 150 fan coil internal units. Mechanical ventilation is provided to some areas only by five AHU's fed by air-cooled water chillers and gas-fired condensing boilers. A BMS performs complete monitoring and management of the building services (HVAC, fire prevention, security, lighting). Energy performance data acquired by the BMS have been recorded and stored since 2005.

The data records indicate that, in the initial operation period, the HVAC system was running 24/24 hrs – 7/7 days; the operating schedule was subsequently optimized by introducing nighttime and weekend system set-back criteria. The effects are clearly seen in the graphs of Figure 5. The weekend set-back is reflected in the greatly reduced consumption on Saturday and Sunday, and in increased system consumption on Monday; the night set-back determines an increase of the hourly energy demand in the morning period of working days. Referring to typical winter conditions, the following electric energy consumption reductions are achieved: 9% on working days and 85% on weekends, yielding a 26.7% weekly saving.

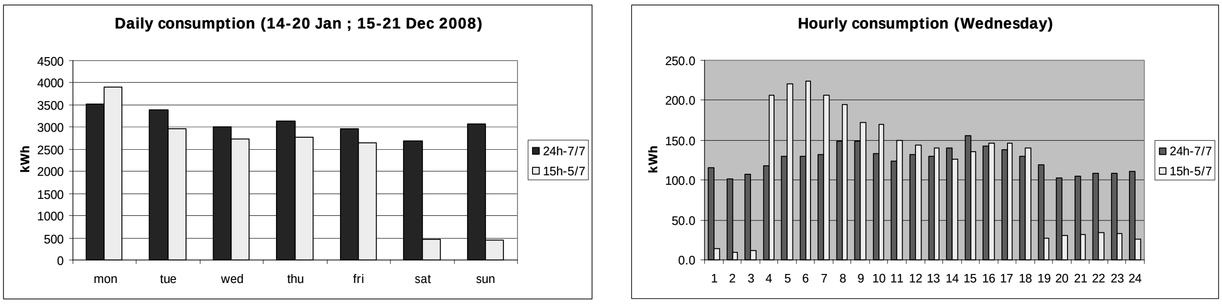


Figure 5. Daily and hourly electric energy demand of VRF system with different schedules

The effects of modified system operation are also well visible in a carpet plot representing the time trend of total electric energy consumption (Figure 6): the plot on the left side refers to a period in which the operation schedule of the VRF system is well defined and stable, while the plot on the right side basically reveals a continuous operation, in which nighttime or weekend setbacks are not clearly applied.

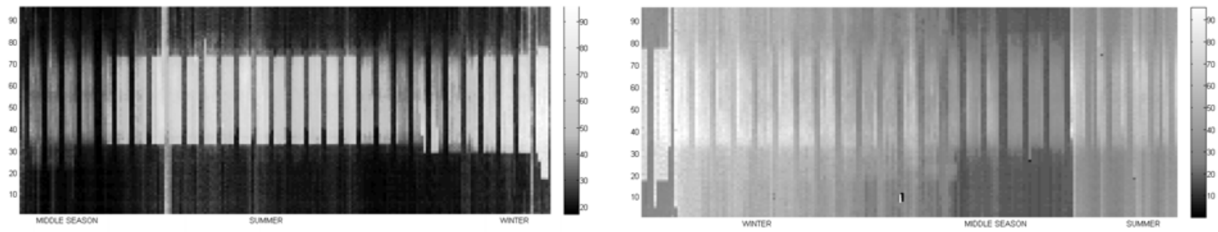


Figure 6. Carpet plots of total electric energy consumption with different VRF schedules

Case study 4: Effect of the operating schedule on a chiller electric consumption

The case study considers a public building equipped with a two-pipe fan-coil system, installed at the time of building construction (1970), coupled to a gas boiler and water-cooled electric chiller; the latter unit was replaced in 2002 and is in good overall maintenance status. In consideration of the low thermal capacity of the building, the study was focused on assessing the effect of a reduced system operational schedule. An electric meter was installed on the chiller, to measure the hourly consumption; the chiller operates six days a week (at reduced load on Saturdays), while it is completely shut off on Sundays.

Three different operating schedules, each applied for about four weeks, were adopted to investigate the effects of varying the chiller on-period: A: 11 hrs ON (7:00-18:00); B: 14 hrs ON (6:00-20:00); C: 10 hrs ON (7:00-17:00). The monitoring results are summarized by the three energy signatures of Figure 7, each referred to one of the chiller operation schedules. The temperature dependence of electric consumption is fairly linear, with acceptable correlation coefficients (particularly for schedules A and C), and exhibits comparable trends, ranked as expected for increasing operation ON-times. Taking into account the statistical distribution of temperatures, it that, by reducing the chiller operation time from 14 hrs/day (B) to 11 hrs/day (A), a 20.7% reduction of chiller mean daily consumption was achieved; a further reduction to 10 hrs/day (C) increased the savings to 22.1%. These values correspond to average savings of 6.2% per hour of daily operation reduction.

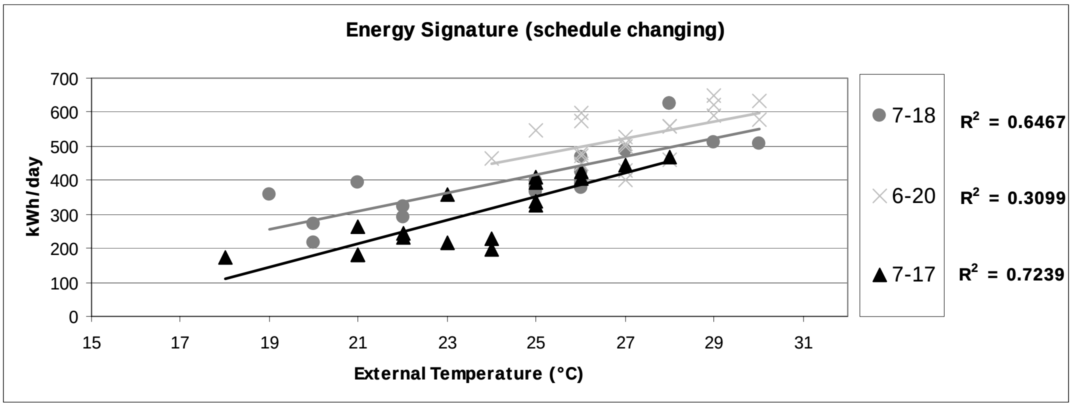


Figure 7. Chiller electric consumption vs daily mean external temperature

CONCLUSIONS

The results obtained so far by the HARMONAC project have demonstrated that an effective approach to HVAC system inspection and energy auditing requires a sound basis of measured primary energy consumption data, which may be difficult to obtain when electrically-driven components are concerned. The availability of properly designed and installed BMS, in conjunction with the installation of a limited amount of relatively low-cost dedicated measurement equipment, is generally sufficient to obtain a clear picture of the energy performance of typical HVAC systems of tertiary buildings. Starting from the analysis of such data, simple ECO's (mostly related to system operation and maintenance) may be readily identified and implemented at very low or even negligible costs. The primary energy savings that such ECO's can yield are typically in the 5%-25% range, but may be as high as 60% under very favorable circumstances.

ACKNOWLEDGEMENTS

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