Real-life assessment of household appliances

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Abstract. The rising demand for energy and the significant contribution of residential buildings to total energy consumption poses a significant challenge in the European Union. However, existing energy efficiency labels for household appliances often fall short of accurately representing these appliances' real-life energy efficiency and performance. Addressing this gap, this study proposes a framework for real-life energy consumption assessment of household appliances, providing a more accurate representation of their performance. It focuses on deploying a sensor-based monitoring system to acquire diverse operational data from various appliances under real-life conditions. The premise is that this real-life data acquisition can lead to a more accurate energy labeling system, addressing the limitations of static energy efficiency labels and offering insights into genuine usage patterns and performance. By proposing a novel real-life appliance assessment framework, this research holds significant potential to enhance residential energy efficiency, facilitating more informed decision-making and promoting sustainable practices.

Keywords: Appliance monitoring · Real-life Assessment · Energy label.

1 Introduction

With economic and lifestyle growth, energy demands are rising as well. Buildings across the European Union (EU) are responsible for nearly 40% of total energy consumption and for 36% of total carbon dioxide (CO_2) emissions [**eu-2018-844**]. Energy reduction is one of the major priorities for the EU. It has issued a legislative framework to reduce greenhouse emissions by at least 40% and increase energy efficiency by 36% compared to 1990 [**eu-2019-175**]. Residential buildings and their energy-consuming equipment are responsible for much of the total energy consumption. The EU has introduced energy labels for domestic appliances to promote energy savings in the residential sector. Recent energy label has a scale ranging from `A` – meaning most efficient, to `G` – least efficient in the market [**sola2021promoting**].

Although statistics show that consumers tend to purchase appliances with a higher energy efficiency evaluation, the label hardly represents an appliance's real-life energy efficiency and performance. For example, a small set of experiments are performed using the program "cotton 40" to assign an energy label to a washing machine. It is based on the reasoning that it is the most popular washing cycle [**euconsorg2017**]. This fact constitutes a rather unfair and limited comparison basis. Possibly, the label should reflect the utilization of multiple cycles and under different loads.

Furthermore, some programs do not reach the temperature advertised on the label. For example, for the program $60^\circ\ C$, manufacturers are allowed to reach only $45^\circ\ C$. This laxity in the standard provides misleading information to consumers since energy efficiency might be better at the cost of lower performance [**euconsorg2017**].

Some studies [**biglia2021real**, **biglia2020energy**, **palmerfurther**] show that energy consumption in a real environment is higher when compared to the laboratory conditions or as anticipated during the appliance design phase. In laboratory-controlled perfect conditions, the appliance might reach an efficiency label such as "`A`". However, when operated in a real household environment, the efficiency level might drop due to various influences. For example, in a washing machine, it is unclear how it would behave under different washing loads, the influence of ambient temperature, degradation over time, and faults that could result in higher energy consumption. Hence, a real-life energy consumption representation is necessary. This new label would consider all the dynamic aspects that are impossible to represent in a static label.

To accurately measure the energy consumption of household appliances in everyday use, it is crucial to employ practical methods and tools for assessing their energy efficiency and performance. The shift towards smart energy solutions enables the management and monitoring of energy resources in real-time, benefiting building owners/managers, intelligent grid operators, as well as consumers and producers alike. We can make more informed consumer decisions and implement operational adjustments by comprehending how real-life environments and usage patterns affect energy efficiency and appliance performance. Furthermore, this allows for the seamless integration of appliances into the energy resource management tools used within buildings' operational cycles.

The main objective of this work is to define a framework for a real-life appliance assessment. It will allow a better understanding of energy consumption patterns under real-life usage conditions. The first step is to implement a device monitoring system that will monitor and collect the necessary information to perform assessments and provide a real-life consumption-based energy label considering dynamic information of the appliances' behavior. However, this paper focuses on the primary stage of this work, which is the residential appliance behavior data acquisition system under real-life conditions. It will provide necessary data for further appliance assessment exploration and real-life label definition.

2 System architecture

Effective monitoring systems have become paramount in today's interconnected world. This paper proposes a monitoring system that provides comprehensive and reliable insights into various aspects of household-monitored applications.

Our system offers a robust solution for capturing, processing and interpreting data in real-time by leveraging advanced sensor technologies, data acquisition mechanisms, and intelligent analytics.

To reach an accurate appliance energy consumption assessment, a monitoring system is needed that could record various measurements, including ***energy, operational*** *and* ***environmental readings***.

From the energy perspective values such as current, power, voltage, active power, frequency, and can be measured using a combination of current and voltage sensors. However, some appliances are more complex than others, for example washing machines, dishwashers, or dryers, hence, it is needed to acquire additional information of operational patterns of the appliances. Taking washing machine as an example, water inlet/ outlet patterns and water quantities measurement are necessary to acquire. The inlet water typically heats up in the tub using a heating element, various programs have different water heating levels, to measure the actual heat of the water, a temperature sensor is necessary to be attached, most accurate temperature can be measured by attaching sensor to a bottom of the tub. Additionally, water temperature monitoring near inlet valve and drain hose is also needed to understand water heating patterns. Furthermore, due to moving tub, machine produces oscillation that might produce additional information such as spinning speeds and load mass of the cycle, hence, vibration measurement must be considered.

Additionally, the appliance performance might be affected by environmental factors that needs to be considered, for example ambient temperature and humidity can have an impact to appliance performance and efficiency. For water consuming appliances, water pressure is an important variable. For example, low water pressure in the household might affect the behavior of the appliance that is not easily noticeable without monitoring solutions.

With a primary focus on acquiring quality data, our system can detect and analyze diverse parameters, such as electric, environmental, and contextual, which are translated into three different assessment levels: reference, actual, and contextual.

– **Reference Assessment**: This type of assessment is related to reference appliance data provided by the manufacturers and stored in the EPREL database. Additionally to the reference data, data related to water consumption and temperature, noise, and oscillations will also be acquired.
– **Actual Assessment**: This type of assessment is related to assessing the actual operating conditions of the appliance, which depend on the use of each household. The operational conditions may differ from the ones used for the Reference Assessment.
– **Contextual Assessment**: This type of assessment is related to the user feedback on the delivered service of each type of appliance. User feedback essentially means that users start to possess an active approach concerning the energy use of the residence. This makes it possible to trigger energy savings thanks to the actions stimulated by a set of collected and processed energy consumption information and the consequent user actions.

Gathering and analyzing data from various sensors and appliances is required to draw a complete picture of each appliance's energy consumption and performance. These data will be used to identify energy usage patterns and develop a comprehensive understanding of how different factors, such as time of day and usage frequency, impact energy consumption. Based on the outcomes of the analysis, a standardized real-life energy labeling approach will be driven to accurately reflect each appliance's real-life energy profile.

Sensor Type	Sensor Model	Measurement Type	Units	Communication Type
		[HTML]E2EFD9**Energy**		
Current Sensor	PZEM-004T	Power	Watt (W)	Serial via UART
		Energy	Kilowatt-hour (kWh)	
		Current	Ampere (I, i)	
		Voltage	Volt (V)	
		Power Factor	PF	
		Frequency	Hertz (Hz)	
		[HTML]E2EFD9**Operational**		
Water flow	FS-300A	Flow	Liters per second (L/S)	Pulse Output
Water volume		Volume	Milliliters, Liters (mL,L)	
Accelerometer	ADXL-345	Acceleration	Standard gravity (g0). X, Y, Z axis.	I^2C
Temperature	DHT22	Temperature	Degree Celsius ($^\circ C$)	One-Wire
		[HTML]E2EFD9**Environmental**		
Temperature	SHT35	Temperature	Degree Celsius ($^\circ C$)	I^2C
Humidity		Relative humidity	Expressed in %	
Water pressure	SEN0257	Pressure	Megapascal (MPa)	Analog

Table 1. Sensor & Measurement List

2.1 Sensor data acquisition and Assessments

This monitoring platform required dimensions that were designed during requirements phase and are necessary for appliance assessment, namely: energy, operational and environmental. Considering each dimension, a specific sensor or set of sensors is required to acquire the data and evaluate the performance of an appliance according to the dimensions. A `PZEM-004T` digital current sensor was selected for energy monitoring. Many of the energy monitoring projects reviewed in related work used multiple sensors to monitor electricity, mainly two sensors, one for current measurement and the second one for voltage in the power line measurement. `PZEM-004T` provides both measurements in one module. From a wiring perspective, it is slightly more complicated to set it up than other sensors. However, the study done by Khwanrit et al. [**Khwanrit**] shows that this sensor has a superb metering accuracy of ± 0.5%. The sensor provides considerable energy features like *RMS Current* (I), *RMS Voltage* (V), *Power* (W), *Energy* (kWh), *power line frequency* (Hz), *power factor* (pf) (that is used to determine the energy efficiency in the circuit, it is a ratio between true power and apparent power). The sensor communicates using the UART communication protocol with a baud rate of 9600 via serial receiver RX and transmitter TX ports. It will be used with all energy-consuming household appliances of interest. After setting up the sensor, it is placed between the appliance and the wall socket to measure energy consumption. Functional boundaries of the sensor:

- rmsVoltage. Measuring range: 80 - 260V, resolution: 0.1V.
- rmsCurrent. Measuring range: 0 - 100A, starting measure current: 0.02A, resolution: 0.01A.
- Active power. Measuring range 0 - 23kW, starting measure power: 0.4W, resolution: 0.1W.
- Power factor. Measuring range 0.00 - 1.00, resolution 0.1Hz.
- Active energy. Measuring range 0 - 9999.99kWh, resolution 1Wh.

Water consumption patterns for appliances that use water are monitored using flow sensors. In a washing machine, the inlet and outlet water patterns and volumes are being measured. A `FS-300A` water flow sensor was selected to measure water patterns and quantities. It is based on a hall effect sensor and produces a square wave pulse when water passes through the sensor. This sensor is highly accurate. However, it requires calibration. Typically, pulses must be converted into actual litres per minute or millilitres per second. Technical features of `FS300A G3/4` flow-meter:

- Flow range: 1-60 L/min
- Working pressure: $< 2\ Mpa$
- Operating temperature: $\leq 80^\circ\ C$
- Liquid temperature: $\leq 120^\circ\ C$

The working water inlet/outlet temperatures of every type of appliance are important. To make these measurements, a DS18B20 digital waterproof temperature sensor is used. The sensor supports 1-Wire communication, meaning multiple sensors can be connected under the same bus. Based on the manufacturer's provided technical sheet, the sensor temperature measuring range: $-55^\circ\ C$ to $+125^\circ\ C$, with an accuracy of $\pm 0.5^\circ\ C$. Furthermore, complex appliances such as washing machines heat the water inside the tub. Since the system is deployed in real homes, installing a sensor inside the tub is impractical. A temperature sensor is installed in the washing machine's glass door as a workaround. This temperature is monitored to capture the heating patterns and temperatures of multiple washing cycles and options of each program that the user can select. Besides the glass door's temperature, the temperature of the inlet valve and drain hose are also measured in the washing machine. In the case of the dishwasher, for example, the only temperature reading made is from the side panel.

Appliances such as washing machines, dishwashers, and tumble dryers have rotary parts that cause machines to oscillate. These oscillations might contain valuable information that can be later extracted from the measurements using vibration sensors. For example, in washing machines, this data can provide information related to the machine's load and tub rotation speeds and disclose unusual patterns that can indicate a fault of the rotary mechanism, an unbalanced load, or a poorly levelled appliance that can escalate to critical machinery fault. Hence, vibration monitoring data is rich in various information about the operational state of the appliance. Three `ADXL-345` tri-axis digital accelerometer sensors are used in each machine to monitor vibrations. This sensor has a full-scale programmable resolution range of $\pm 2g$, $\pm 4g$, $\pm 8g$, and $\pm 16g$ and communicates using an I2C bus protocol. It supplies data of three axes oscillations, in the X, Y and Z-axis. The monitoring system acquires data from the sensor at the frequency of $200Hz$, producing 12000 time series data points per minute per each axis per sensor.

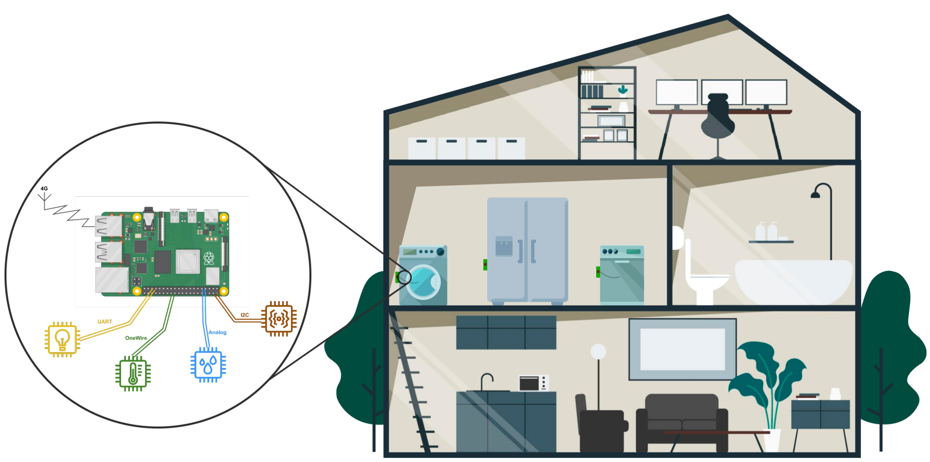

Fig. 1. System Contex

For the environmental dimension, ambient temperature, humidity, and water pressure were considered. An `SHT-35` digital temperature/humidity sensor is incorporated into the monitoring solution to monitor ambient temperature and humidity. This sensor is fully calibrated, linearized, and temperature compensated, producing digital output. It communicates via I2C bus protocol. It has a high accuracy grading of ±1.5% relative humidity (RH) and ±0.2 °C ambient temperature. Its temperature measuring range scale is from $-40°$ C to $90°$ C. Furthermore, water pressure is measured using a Gravity analog water pressure sensor (AWPS). Its measurement accuracy is 0.5% 1% (0.5%, $0 \sim 55°$ C). The sensor's output is analog and outputs a voltage converted into a water pressure measured in megapascal (MPa).

2.2 Monitoring architecture

The centre of the architecture is the single-board computer . It collects and records data in real-time from the array of sensors specific to the appliance in question, each capturing a unique dimension of appliance operation. This information is then written to Raspberry Pi's internal storage, acting as a local buffer for the acquired data. Periodically, a process is initiated that sends this locally stored data to a central server.

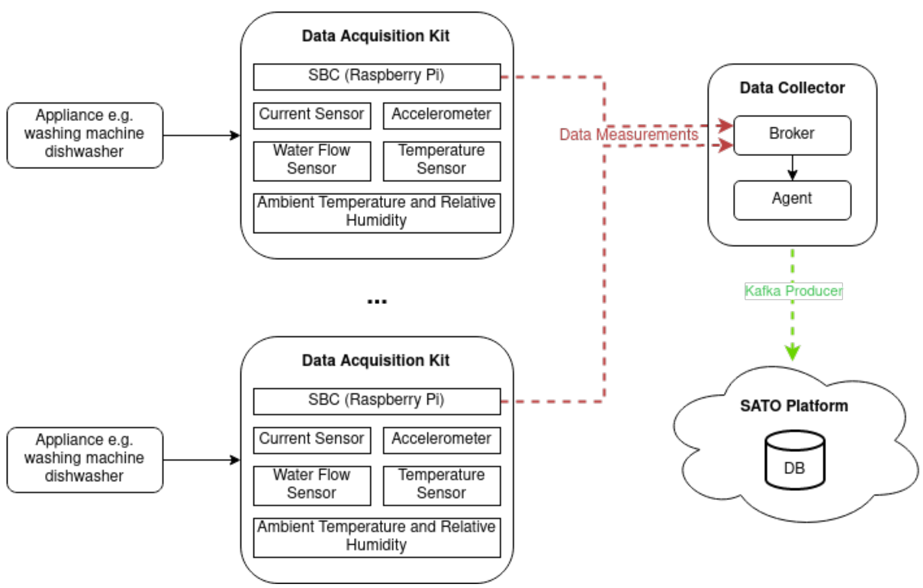

Fig. 2. System Architecture

Making use of this mechanism provides a double safeguard. While ensuring the continuous acquisition and storage of data even in network outages or interruptions, it also reduces the number of times the computer establishes a connection to the server. Reducing the number of attempted connections is important because 4G connectivity was chosen. Since the reliability of establishing a connection is lacklustre in these networks, maximizing the amount of data transmitted when a successful connection is established is paramount. Figure 2 gives a top-level overview of the architecture and its deployment.

3 Data

To communicate with the sensors, it is necessary to connect them to either a microcontroller unit (`MCU`) or a data acquisition (`DAQ`) board. An `MCU` approach was adopted in the household deployment. Since the deployment is to be made in real households, a small kit containing all the necessary equipment is preferable. The best solution is to use a single board computer (`SBC`) that can handle all the needed connectivity and reduce the amount and size of the hardware used. To this effect, a `Raspberry Pi 4 Model B (4GB)` was selected. This `SBC` features a 40-pin GPIO (general-purpose input/output), a 64-bit quad-core processor and dual-band wireless LAN (among others). Providing this functionality in a small package makes it ideal for this type of application. It supports high-speed analog inputs, analog outputs, and digital communication protocols, such as I^2C, One-Wire or Serial communication. The GPIO pins provide all this connectivity and have more than enough IO for the (up to) 1807 measurements per second needed. Table 2 shows the number of each sensor type installed in each type of appliance and the number of measurements per second taken for each appliance.

[HTML]E2EFD9 [HTML]000000 **Type** [HTML]E2EFD9	**Measurements per Sensor**	[HTML]E2EFD9[HTML]000000 **Measurem per seco**
Water Flow	1	1
Temperature	1	1
Accelerometer	3	200
Current	1	1
Ambient Temperature/ Humidity	1	1
Water pressure	1	1
Temperature (Wireless)	1	1
[HTML]C0C0C0	[HTML]C0C0C0Measurements per second:	1803

Table 2. Sensors per Appliance

After acquiring the desired measurements, these are written to the persistent memory of the `SBC`. The type of encoding chosen is `JSON`, mainly for its versatility and ubiquity. Periodically, this data is transmitted to a SATO platform server. This data is then decomposed into each second of measurements and inserted into the prepared databases.

4 Conclusions and Forthcoming Work

In conclusion, this article has highlighted the limitations of the current energy labelling system for household appliances and proposed a framework for creating a real-time energy label. The framework emphasizes the need for accurate energy consumption and performance representations under real-life conditions. The proposed system aims to gather comprehensive data and provide a holistic understanding of energy usage patterns using practical methods and sensor technologies. Through data analysis and machine learning techniques, the framework intends to develop a standardized real-life energy labelling approach that goes beyond static measurements. This work can potentially improve energy efficiency, enable informed decision-making, and promote sustainable practices in the residential sector. Future work will analyse the collected data and develop a standardized real-life energy labelling approach. By processing and interpreting the data, the framework aims to identify energy usage patterns and understand the influence of different factors. The insights gained from this analysis will contribute to developing a more accurate energy label that reflects the dynamic aspects of appliance behaviour. Additionally, integrating appliances into energy resource management tools will optimize energy usage and benefit building owners, managers, and consumers. The forthcoming stages of this work will involve thorough data analysis, model development, and validation to create a practical and reliable framework for enhancing energy efficiency and promoting sustainability.

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