Development of an Open-Source Smart Energy House for K-12 Education

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***Abstract*—Energy consumption in buildings represents about one-third of the world-wide energy consumption. Consumers often are not fully aware of energy-conserving measures they could take. Intelligent control of the heating and lighting systems in buildings is one way to increase energy-efficiency. Children and young adults influence domestic energy consumption, by using appliances such as TV and lighting. Often, they are not aware of the costs incurred. The goal of this research is to develop a educational platform for energy efficiency education aimed towards the full age range of K-12 education. A scaled model of a house is used, to explain the energy flows in the residential setting, well-known by the target audience. A model house is designed, with actual loads, using an Arduino Uno electronics platform as an interface to a PC. A reference program in the integrated development environment S4A allows visualizing the energy consumption in a simple manner. The children control a number of scaled household appliances interactively. A survey with the first 25 children (aged 10-12) suggests higher awareness of energy consumption.**

***Index Terms*—Energy education, energy management, microcontroller, open-source**

I. Introduction

ENERGY use in the buildings sector, including residential and services sub-sectors, accounts for 32 % of the total consumption world-wide [1]. Reducing the use and increasing the efficiency is a major driver for new technologies and living concepts. European directive 2002/91/ec [2] sets energy benchmarks and goals for energy efficiency at the level of buildings. By 2020, all new buildings would be nearly 'Zero-Energy Buildings' according to recent European recast 2010/31/eu [3]. Lighting has an impact on the thermal management system in buildings. Efficient lighting means less heat is generated, decreasing the operating time of air conditioning equipment and causing additional savings.

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In many places around the world, incandescent lighting are becoming banned, because of the low efficiency. For example, through European commission regulation 244/2009 [4], recently all sales of incandescent light became banned in Europe, with estimated savings of close to 40 TWh/year. The United Nations Environment Programme 'en.lighten' aims to promote, coordinate and accelerate the efforts to roll out energy efficient lighting for developing and emerging countries [5]. Their research states that world-wide, 939 TWh of electricity - equal to 5 % of electricity consumption - could be saved annually, by replacing inefficient lighting.

The electricity consumption of other household appliances also is an important issue. Commonly used appliances such as dishwashers, televisions, refrigerators, tumble dryers and washing machines must provide energy efficiency information in a standardized way to the buyer through energy labels [6]. To make informed decisions, it is critical that buyers understand the information that is provided to them. In spoken English, 'power' and 'energy' are used interchangeably, causing confusion on what is actually addressed. The units 'kW' and 'kWh' are often mistaken by people who are not familiar with the topic. Education is important improve awareness of energy related issues and to obtain the wanted energy-saving behavioral response with minimal rebound effect [7].

Children have an intuitive understanding of the difference between power and energy. Even at a young age, they understand it quickly when riding a bicycle. When riding, they provide power to keep moving. The longer they ride, the more energy they need and the more tired they feel afterwards. However, the imaginative leap needed to understand power and energy use in heating and lighting systems at home is big. Therefore, an educational platform that allows children to experience and interact with a residential energy system is considered in this paper.

In this paragraph, a discussion of identified educational tools is given. Reference [8] creates educational tools surrounding energy for K-12 (primary and secondary) eduction, with strong restrictions on age or topic. Reference [9] creates informative boxes, with predetermined lessons for limited target age group. Reference [10] provides free lesson plans with relation to residential energy, for limited age groups, without full scope approach. Reference [11] offers educational kits, with a limited topic, limited adaptability. Reference [12] offers an educational

kit on sustainable living, at high cost with little creative possibilities or interaction. Reference [13] provides limited scope platforms with high cost and education barriers. It is concluded that no available product offers the combination of realism, adaptability, broad age range, student generated content and open design.

The goal of this research is to develop an educational platform for energy efficiency education aimed towards the full age range of K-12 education. A scaled model of a house is used, to explain the energy flows in the residential setting, well-known by the target audience. Through an interactive display, the energy flows in the real-world model are to be controlled and shown in real time.

In Section II, the design requirements of the platform are determined, to maximize the availability and reusability. In Section III, the design is proposed and its properties are discussed. In Section IV, the organisation of a workshop using the platform is detailed. Finally, Section V provides conclusions and discusses further work.

II. Design Requirements

Three considerations defined the design requirements: broad age range of the target audience, maximum reach and the practicality of the platform.

A. Broad age range of target audience

The increase of energy efficiency in a residential context is of interest to all ages and educational levels and backgrounds. To maximize the benefit on the effort of this design, the target group of the platform is K-12 education. Creating a platform for such a wide age range, especially on the lower end, implies certain requirements.

1) Safety: The whole of the platform must be safe to operate by children with limited supervision. This implies that used voltage range is low safety voltage, used materials are non-toxic, edges are dull, temperatures are below skin damage tresholds, etc.

2) Size and weight: To be easily manipulable by children as well as adults, all parts that require physical interaction must fit comfortably in both small and large hands. The weight of the physical parts of the platform may not be restrictive for children to manipulate it.

3) Durability: The children's coordination skills or playfulness may not be a barrier to longevity of the platform. The physical parts of the platform should withstand typical drops, wrong operation, even creative play, without significant damage or effects on the functionality of the platform.

4) Language: The platform must be available in the language of the user, so that the focus of the learning experience stays with the topic. This implies that the tool must not only be available in multiple languages, but changing between languages must be possible, for international teaching settings. Visual communication with the platform is advisable.

5) Hands-on visual experience: Many children, especially younger ones, feel more captivated with abstract concepts when the application is clear, they can contribute to the education and physically interact with the teaching platform. Therefore, the platform must be based upon the physical interaction by the students on an application of the abstract concepts. This physical interaction must create immediate visual responses in the platform, to maximize the engagement.

B. Maximum reach for target teachers

To maximize the possibility for teachers to use this platform for as many children as possible, two main issues determine the design requirements. First, the teachers must access the platform in some way, acquire it, before teaching can be realized. Second, once acquired, the use- and reusability of the platform must be as high as possible.

1) Access to platform: Increase the access to the platform, all barriers to acquiring such a platform must be low.

a) Cheap: As educational institutions are typically constraint in their budget, the cost of the platform must be low for its educational value. Also, the target audience is not limited to educational institutions, but open to anyone interested in the topic. The costs should be so low that the acquisition of the platform is interesting, regardless of future benefits related to the education.

b) Open-source: All parts of the platform, both physical and software, are provided as an open-source platform. Teachers may freely use, copy or expand upon the provided material. Full information on design and methods is necessary.

c) Reproducible: The goal is to educate; acquisition of the platform is not, and might even create a barrier. The open-source design must also be reproducible. Therefore, all physical components must be reproducible using a widely available and inexpensive tools or infrastructure.

d) Simple to repair and reproduce: Skills required to repair or reproduce should be low, and within limits of children with adults assistance.

e) OS independent: Different educational institutions have different software policies. Providing that some parts of the platform will be software, they must run independent of the operating system.

2) Reusability of tool: Once acquired, the platform must create as much educational value as possible. This demands that the platform is used by as many as possible for as much education as possible.

a) All ages: The tool must provide educational value for all ages of the range. Without modification of the physical components, it must create challenges of multiple levels.

b) User generated content: As interest of students and teachers changes, or local conditions are different, adapting the platform to these new requirements must be possible. These adaptations must be easy to realize, and not require much experience with the platform. Teachers as well as students may add new functionality themselves, expanding the learning experience to their interest and understanding.

C. Practical

A platform that is easy to use, prepare, maintain will be more effective. Practical considerations related to education create specific design requirements.

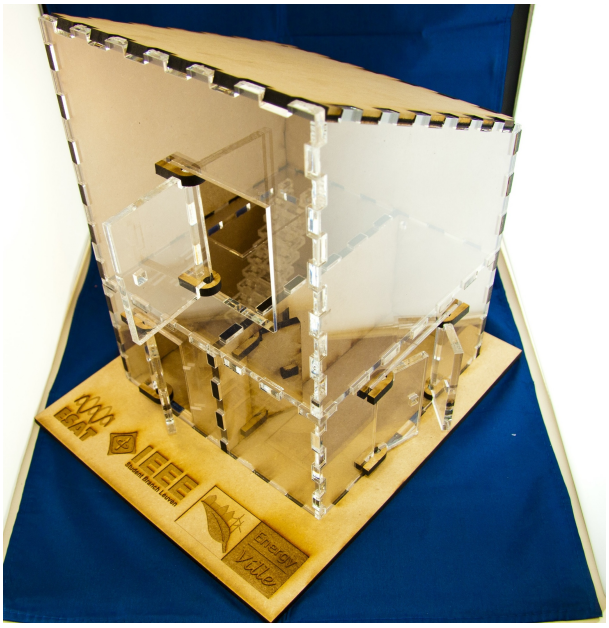


Fig. 1: The Smart Energy House educational platform.

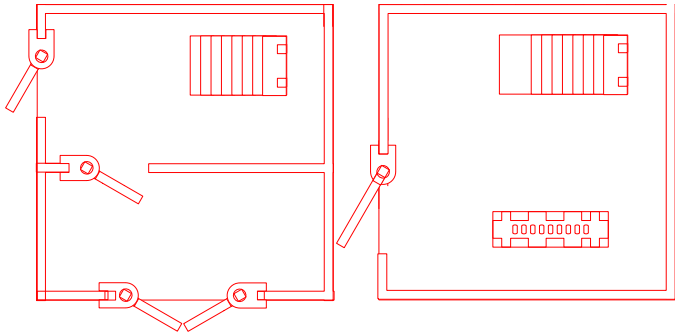


Fig. 2: Top-view, ground floor left, first floor right. Doors, windows, staircase and heater visible.

1) Compact storage: Educational institutions use reconfigurable spaces to teach different topics at different times. The platform will not be used constantly, and must be easily stored in a compact form.

2) Transportable: Education typically takes place at fixed locations. A significant part has however large transportation distances. To use the platform in such conditions, it must be easily transportable, restricting the size and weight of the stored platform.

3) Robust: Education wears and tears material. The platform must be designed to withstand this wear without change to the functionality of the platform. Physical and electronic components will continue to realize their educational function, without tuning to conditions.

III. Design

In this section, the design choices made are explained, based on the requirements determined in the previous section. In the present design, a heating and lighting system is included, as well as temperature and power measurements. The remainder of the paper will focus on this setup.

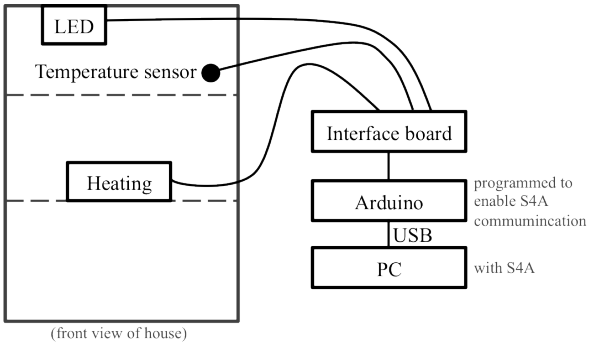


Fig. 3: Smart Energy House architecture.

A. Mechanical design

The energy house is designed at a scale of 1/24. The largest piece is 30 cm by 25 cm (base plate) and the smallest is 2.6 cm by 1.7 cm (window hinge), which facilitates manipulation by children's hands. To be able to look into the house, two walls and the intermediate floor are manufactured from acrylic glass. A constructed house can be seen in Fig. 1. The ground floor has two rooms: a garage and an entrance hall with stairs to the first floor. The first floor is a single big room with a window. It is easy to install the heating and the lighting systems by temporarily removing the roof. A floor plan is given in Fig. 2.

The mechanical components (walls, furniture and windows) are designed to be easily modifiable and reproducible in a 'fab lab'. There are numerous fab labs around the world, offering infrastructure such as laser cutters and machining tools to make almost anything [14].

The developed design can be reproduced without modification in laser cutter which can cut 300 mm x 600 mm x 6 mm medium-density fibreboard (MDF) and acrylic glass (AG). Teeth are used so the house can be assembled without tools. As no glue is used, the house can be disassembled, stored and transported efficiently. MDF and AG are robust, inexpensive and light-weight materials. AG is brittle, however still safe to use with children. It does not shatter but may break into large dull pieces when stressed.

B. Electrical design

A power supply voltage of 12 V is chosen. Such low voltages are safe to touch, but it is still practical enough to supply power for electric heating. To find power supplies of manageable size, a 2 A current limit is chosen.

Arduino is an open-source electronics prototyping platform with a microcontroller, designed to inexpensive and approachable to people with very limited experience with electronics [15]. A number of analog inputs, digital inputs/outputs (I/O) and pulse-width modulated (PWM) outputs are available. The microcontroller platform has a USB socket can be programmed through a computer, without an external programmer. Specifically, the chosen Arduino Uno platform with an Atmel AVR ATmega328 micro controller. Other models are available with e.g. other form factors and more processing power or I/O-channels. The Arduino Uno has 6 analog inputs, and a total of 14 I/O pins of which 6 provide PWM output.

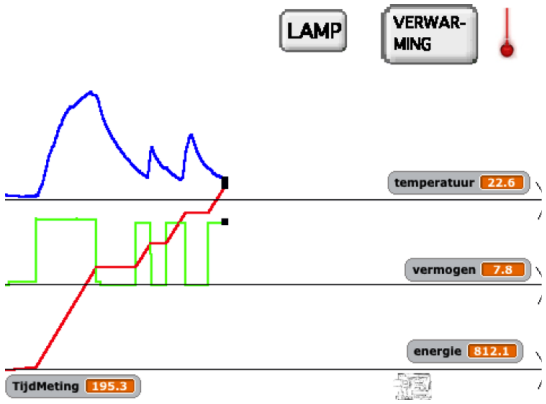


Fig. 4: Screenshot of S4A visualization: indication of energy, power and temperature (in Dutch).

The operating voltage is 5 V and the current of the I/O is limited to 40 mA. The Arduino Uno can interact with a PC through serial communication (RS232) over USB.

A Negative Temperature Coefficient (NTC) resistor is used to measure the temperature. At the 12 V side of the power supply, a resistor is put in series to create a voltage divider. This way, the Arduino can easily measure the voltage over the NTC resistor. Because of the limited number of available channels, and to allow for future integration of more sensors, not all of the electrical parameters are actually measured. For instance, the current through the electric heating system is not measured. However, the voltage of the power supply is measured. Because the resistance of the heating is known, power consumption in the heating can be calculated with a resolution fit for the application.

The resistive heating systems uses a 18 Ω 10 W resistor. At 12 V, the heating power is 8 W. The lighting system uses white LEDs. The supply voltage is too high to use without series resistance. To improve the efficiency, LEDs are connected in series. A MOSFET is used as a relay to switch the household devices through the Arduino. The IRFU3707PBF MOSFET has a threshold voltage V_{gs} of only 3 V, which leaves enough margin from the 5 V supplied by the Arduino. The maximum switching is I_d = 61 A and V_{ds} = 30 V. As the power supply voltage is 12 V, it is possible to control the lighting as well as the heating through this setup.

The sensor board uses a lock-key system for the device connections, to avoid damaging the devices of the electronics. Through a voltage divider, the power supply voltage is measured. The sensorboard, the heating appliance and the Arduino controller board can be seen in Fig. 3.

C. Programming

Scratch is a programming language learning environment, designed to allow children to intuitively create and design computer programs [16]. In this graphical programming environment, a computer program is constructed by drag and drop using the mouse. Syntactic problems are avoided by using different colours and shapes for functionalities. The building blocks to create a program fit together only when the code is syntacticly sound. S4A (scratch for Arduino) is a project based on Scratch which allows interfacing with Arduino [17]. Through Arduino, programs can be made which interface with the physical world through sensors and actuators. The Arduino hardware is programmed using a language similar in syntax to C++, with some simplifications and modifications. An integrated development environment (IDE), also named Arduino, is available. It provides a basic code editor and single click code uploading to the Arduino hardware.

First, for S4A to work, a program has to be uploaded through IDE to the Arduino hardware. This program communicates set points and measurements with S4A through the USB connection with the PC. This process happens on with a period of 75 ms. At this time, it is not possible to reconfigure the I/O channels within S4A. Some of the channels are hard-coded to be inputs and others to be outputs.

A base program has been written in S4A to take care of simple tasks, e.g. sensor reading, actuator control and calibration. It also provides the methods for power measurement and energy consumption calculation, and variable price communication. Other functionality, such as lighting control and thermostat functionality are implemented by the workshop attendees. Fig. 4 shows the energy metering information as visualized in S4A. The top graph shows the temperature profile (°C). The middle graph shows the total power profile of the household (W). The bottom graph shows the cumulative energy consumption (J). Similar information is typically shown on in-home displays for smart meters.

D. Discussion

The house, including the electronics, weighs 2.6 kg and fits in a box of size 11 cm x 36 cm x 26 cm. Three plates of 300 mm x 600 mm are required: two wooden ones a single acrylic glass one. Total laser cutting time is 2.5 h. Fab labs often offer laser cutters compatible with this form factor. Arduino hardware is widely available. The sensor board is soldered manually, using widely available components. Full design details are available at [18].

The most limiting factor of the current platform is the need for an external power supply. A 12 V lead acid battery pack could be used, however, relatively high power is required for the heating system (8 W), meaning a substantial capacity is required. Old computer power supplies offer high currents at stable 12 V voltage and could be used, but safe packaging is a concern. Another solution is using a power adapter.

IV. Workshop Results

The ‘Kinderuniversiteit’ [19] is a annual event organized by the University of Leuven.Several technically inclined workshops are held for children in Dutch, to bring them into contact with science, engineering and academia. The age group for this particular workshop was 10-12 year olds, on the topic of electric heating and lighting in a house.

The attendees worked in teams to build and wire wired the houses with little assistance, as depicted in Fig. 5. Depending on the level of interest of the team, the guidebook was used or neglected. Apart from connection reversals, all systems were build by the attendees without issues. Through the



Fig. 5: Workshop in progress with 10-12 year old attendees.

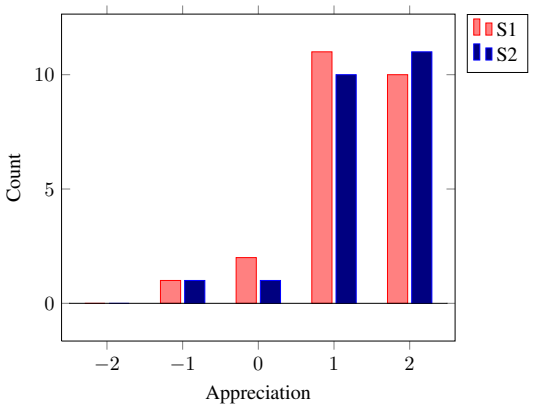


Fig. 6: Survey results of first workshop with 25 attendees; answered on a 5 step scale from very bad/boring/false to very good/fun/true. S1 and S2 refer to the statements.

S4A environment the attendees had to reach a predefined temperature in the house by controlling the electric heater. During the process of the heating, power and energy are explained. During the cooling down, the irreversibility of heating is explained. Next, the attendees attempt to create a simple thermostat, and then the thermal inertia is discussed. The guided experiments allowed for a fun workshop with room for thinkering. Feedback on the following statements was obtained from the children:

- S1. I learned a lot about what a smart meter can do in my house;
- S2. the workshop and the smart energy house helped me to understand this better.

The results of the 25 attendees are given in Fig. 6. From the answers it is clear that the bulk of the opinions are positive or very positive.

V. Outlook

The Smart Energy House is an ongoing project. It showed promising results in the first workshop. It is open-source and designed to be expanded upon. In a next phase, a shield for Arduino will be designed. A shield is a plug-in board for which the pins align with the female headers on the Arduino board. A compact box for the electronics will be used, with external headers for the devices and sensors. The Arduino shield must be designed with mechanically strong connections, have easy color coding, and must be made child proof. Increasing the range of sensors through I^2C digital sensors is possible as well, but currently there is no support in S4A.

Additional power sources are to be considered. As the house has roof space available for a solar panel, it could provide some energy to the house, in reality or simulated based on measurements. Small residential wind mills could be designed for this application. New appliances may be designed, considering both thermal and electrical applications. New devices can be developed within the project community [18]. Heat storage through phase-change materials is possible as well. The thermal time constants of the house are acceptable, but more experiments with insulation should be performed.

Graphical programming languages which provide compilible code for Arduino exist as well, e.g. minibloq [20]. A higher level of programming experience is required, however, stand-alone operation without a PC is possible. Furthermore, additional work is needed to provide display functionality using a PC.

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