The DC House Project: An Alternate Solution for Rural Electrification

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***Abstract*—The DC House project started in 2010 which aims to provide an alternative solution to rural electrification, especially for geographically hard-to-reach areas. The DC House offers an individual or family-based as opposed to the community-based rural electrification. This makes the DC House solution scalable, affordable, and flexible. It does this by operating its components and system based on low-power, low-voltage DC electrical system to directly run DC loads; thus, bypassing losses associated with the traditional AC voltage system. The DC House also uses human-powered energy sources, making it even more sustainable in producing electricity. The development of the DC House system along with its components will be presented. Recent status of the DC House including the various projects undertaken to construct it and plans for its field testing will also be summarized.**

Keywords—DC power, off-grid power, housing, renewable energy, human-powered energy

I. Introduction

Around 1.6 billion people in the world are estimated to live without electricity; many are below the poverty line as listed in Table I [1]. Approximately 2.7 billion people still rely on traditional use of biomass for cooking [2]. This truly alarming statistic raises several questions about the impacts of globalization in many areas of the world. Despite technological advancements in industry, medicine, agriculture and services, electrification globally is still considered severely lacking.

TABLE I. Population Without Electricity

Regions	Millions without electricity
South Asia	706
Sub-Saharan Africa	547
East Asia	224
Other	101

Traditionally, transmission lines are necessary to transmit large amounts of power generated from large scale power plants to regions of high population density who can use the power for commercial and residential applications. However, in many countries a large portion of population without electricity live in remote areas with considerably dispersed population density. Therefore, providing the necessary power grid to these areas becomes a problem of economics. More specifically, the high initial cost of building the infrastructure (substations, transmission lines, transformers, etc.) for a small village of a dispersed people is difficult to justify. In essence, it is prohibitively expensive to bring the traditional electrical grid to remote areas of the world. This in turn creates an opportunity for engineers to apply new technologies to fulfill the empty humanitarian gap that still exists despite globalization and huge strides in the development of technology around the world.

To this day, the primary energy sources for the world come from fossil fuels such as petroleum, coal, and natural gas. These energy sources have been known to cause problems mainly in the areas of sustainability, national security, and global warming.

Fossil fuels are a finite resource inherently making them non-sustainable because they will eventually be completely consumed. There are continuing concerns about the reserve levels of these fossil fuels, and there are many different takes on the remaining quantity. Estimating accurately the levels of fossil fuels is an extremely difficult task because technology is constantly allowing new sources to be tapped. However, it has been estimated that 50, 60, and 200 years left of oil, natural gas, and coal respectively are left at the current rate of consumption [1]. This is somewhat alarming, especially considering that the industrialization of high population countries such as China will increase the consumption rate of these fuels. This further gave rise to finding alternative energy sources such as renewable energy sources to achieve a more sustainable future.

The dependency on fossil fuels may impose national security concern. Looking at the U.S. for example, it has been observed that a disproportionate amount of the remaining fossil fuel reserves is located outside of the U.S. The United States has only 2% of the world's petroleum reserves, and in 2005 for example must import 43% of its annually consumed petroleum from other countries [3]. This creates conflicts of interest for our nation to become reliant on other countries for purchasing fuels in the United States [4].

Based on the results of many studies, fossil fuel consumption is a major cause of global warming which is a phenomenon where greenhouse gases produced from burning fossil fuels such as petroleum and coal warm the earth. This has been known to cause negative environmental effects which affect both human and non-human life on earth. This again provides the motivation to seek for alternative energy sources such as renewable energy sources which do not emit green-house gases.

Renewable energy sources have the potential to provide long-lasting solutions to the aforementioned problems. It is for this very reason many countries in the world have invested in renewable energy to provide an alternative source of energy as reported in [5]. Renewable energy sources have also been utilized in many third world countries for rural electrification such as in Latin America [6], Bangladesh [7], Lao [8], and Indonesia [9]. This makes sense since renewable resources are abundant, locally available, and are fairly evenly distributed around the earth. Even small amounts of energy can make a significant difference in remote rural areas and hence higher costs are justifiable. Furthermore, utilization of locally available renewable resources can create job opportunities and mitigate the trend to mass movement to urban areas.

In recent years there have been intensive efforts to utilize DC in distribution system to supplement the traditionally used AC system. Examples are DC system used in microgrid with renewable energy sources [10, 11], data centers [12], and electric vehicle charging stations [13]. For residential electricity DC system has also been studied as part of the DC microgrid system [14, 15]; hence, the voltage level is still relatively high. For small houses as typically found in rural areas of many third world countries, the use of low voltage system for direct interface or connection to small-scale renewable energy source may offer more benefits than the high-voltage counterpart. The DC House project aims to develop a low-voltage DC electrical system for a single small house mainly to help in rural electrification effort.

II. Benefits of DC System

DC electrical system is not new. In fact, Thomas Alva Edison patented a system for electricity distribution in 1880 which was essential to capitalize on the invention of the electric lamp. In automotive applications such as car or RV, a 12 V DC system with one or more batteries is used to power the on-board electronics and lighting. This basic DC power system is very similar in motivation and function to a power system that incorporates renewable energy sources. It provides a bus voltage that supplies DC powered loads, and via battery provides power to those loads when the energy source is inactive (cloudy weather for photovoltaic generation as an example).

One primary weakness of renewable energy sources is that their operation is not guaranteed based on many things such as weather conditions (with the exception of some such as geothermal). Therefore, they may not be practical if used as the sole energy source for a house. However, this problem may be resolved using a DC system that would integrate renewable energy sources, batteries and DC loads, all into one residential DC system.

Additionally because photovoltaic, small-scale wind and hydro turbines natively output DC power at relatively low voltage, they must be connected to an inverter to produce a relatively high AC voltage so that the energy can be useful to a traditional AC house. This conversion introduces losses that are estimated to be between 23% and 28% [16]. This AC power when used for residential loads are mostly converted back to DC through rectification process inside each load. This further adds conversion losses between 17% and 35% [16]. The use of DC electrical system can help eliminate the wasteful conversion of AC to DC, and in many cases DC to AC prior to entering the house. With the DC House system, it has been estimated that more than overall 15% efficiency improvement may be obtained as compared to its AC system counterpart.

Another problem with the use of inverter is its lifetime due to electrolytic capacitors that are heavily used in inverters. These capacitors are notorious for a short lifespan, typically 5 to 8 years [17]. This necessitates the implementation of maintenance plans that can be costly and will require power shutdown during replacements. With DC system, the heavy reliant on electrolytic capacitor bank may be avoided, thus making residential electrical system more efficient, reliable and economical to operate.

III. The DC House Project

The DC house project is a humanitarian project that aims to replace a traditional off-the-grid AC power house in remote, secluded, or geographically hard to reach areas in third world countries with a house that fully operates on DC electricity. The DC House can accept one or multiple renewable energy sources for its source of electricity. To help minimize the issue with intermittency of renewable energy sources, the DC House can also take in energy from human-powered generators. Figure 1 illustrates the system diagram of a DC House [18].

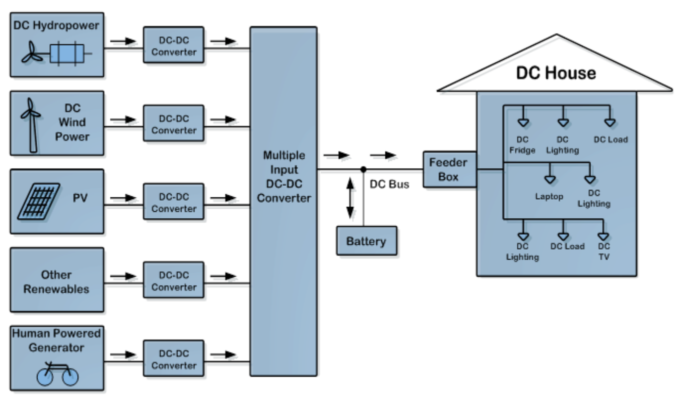


Fig. 1. Overall simplified block diagram of the DC House project

The approach taken by the DC House project is different from the community-based approach commonly practiced world-wide for rural electrification. In contrast, DC House project is an individual or family-based approach to rural electrification allowing people in rural areas the opportunity to gradually educate themselves about the benefits of electricity [19]. With this approach, every person or family in a house unit can start using electricity based on their need and on how much they can afford. This is the main reason that makes the DC House project scalable in power level and flexible, more specifically in terms of how many components the house can use. For example, most families in these hard-to-reach areas are poor, so they can start using electricity in a smallest and simplest way based on what they need the most. For lighting as an example, a portable DC light bulb that is rechargeable by using the sunlight may be a good start. As they begin to appreciate the benefit of electricity and their need to use electricity is growing, they can purchase more of these light bulbs which later can be plugged in to the DC system in their house if they can afford it, or if the system has already been installed.

The DC House project started in 2010 at Cal Poly State University in San Luis Obispo, California and has several phases to accomplish various tasks [20]. As shown in Figure 2, a DC distribution system in DC House serves the simple purpose of delivering power from energy sources through the Multi-Input DC-DC Converter to a set of loads that will in total accumulate to approximately 400 to 500 Watts. The multi-input DC-DC converter takes in one or more inputs from energy sources at different voltage levels and produces one DC output voltage which has been established to be 48 V DC. A DC House must be designed to fulfill the needs that a typical home provides. The house should have the ability to provide for example indoor and outdoor lighting at minimum, food storage capabilities, food preparation options, and many other services.

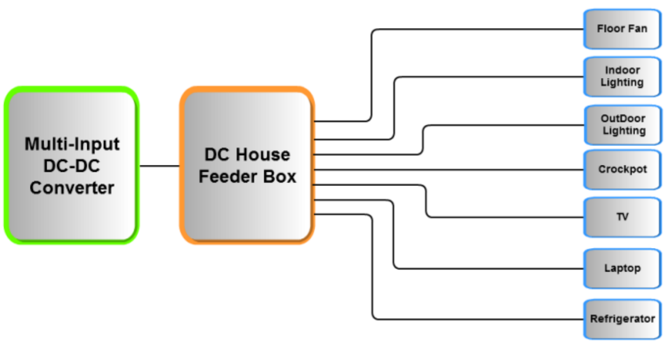


Fig. 2. DC House power distribution

IV. DC House Components

The DC House project offers new opportunities as well as challenges due to its heavy reliant on renewable and human-powered energy sources to provide electricity for a small house unit. The following are examples of DC House components.

A. *Energy Sources*

Referring to Figure 2, the DC House system may incorporate multiple energy sources, mainly from renewables. Renewable energy for power generation is not new; however, low-power renewable energy source for use in small-scale residential system is definitely unique. For example, due to the low-power requirement of a DC House, it is now crucial to be able to harvest energy from common small water streams that are currently not being utilized for hydropower generation. This brought up the idea of portable nano-hydro power generator which takes advantage of small water streams to charge a battery for later use in the DC House. The portable nano-hydro generator is currently being developed as part of the DC House project.

Another source of electricity for the DC House is the human-powered generator. This method as the name implies makes use of human power to generate electricity. The main reason for having such a source is firstly to complement the renewable energy sources that are intermittent, and secondly to promote fun and healthy activities for family while at the same time generate electricity for the house. A common method to achieve this is the human-powered bicycle generator. However, realizing that a family in rural areas of third world countries typically have several children, play park power generator may be ideal since they provide a simple and cheap way of generating electricity. See-saw, merry-go-round, and swing generators are examples of play-park generator components that are currently being developed as part of the project, as shown in Figure 3. Although play-park power generation has been proposed before and is realized to produce small amount of electricity, the energy collected is still meaningful enough to charge small but useful load such as cell phones and rechargeable/portable DC light bulb. This is also better accomplished these days through more efficient power electronics.

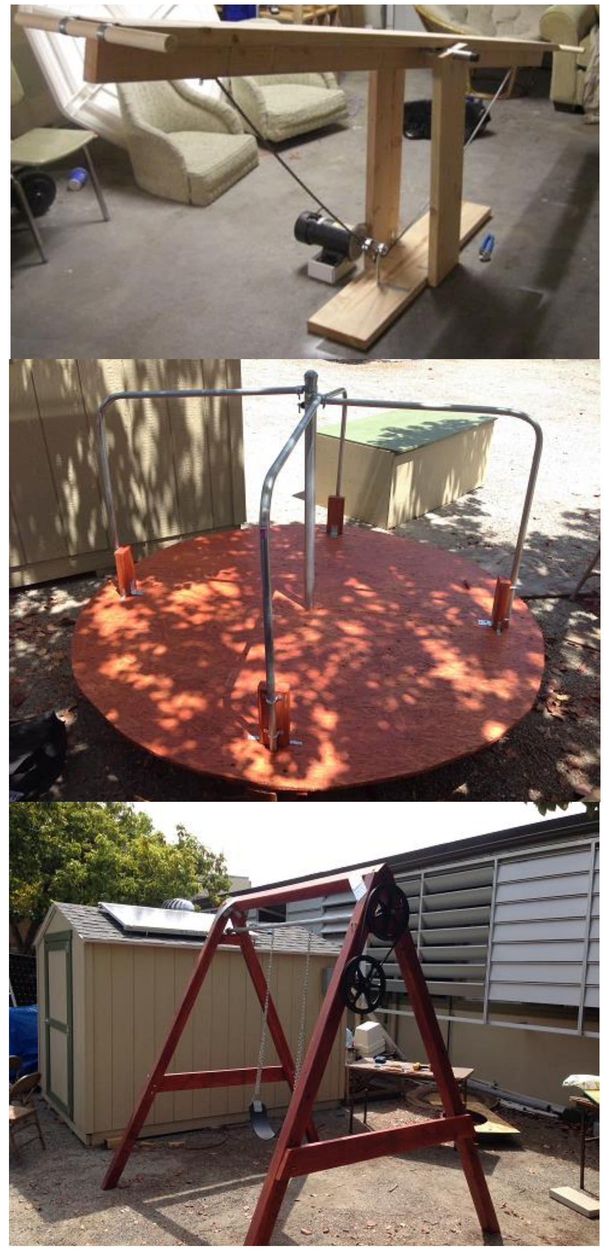


Fig. 3. Play-park generators

B. *DC-DC Converter*

Another component of the DC House is the Multiple Input Single Output DC-DC converter (MISO). The DC House is designed such that it uses one or more renewable and human-powered energy sources to ensure continuous supply of energy.

The multiple sources will interface with the main DC bus of the DC House through a converter that is able to take in multiple inputs from several sources while outputting only one output to the main DC bus of the DC House. The MISO converter shown in Figure 4 offers a more efficient solution than using an individual converter for every source being used to power the house. MISO reduces losses associated with DC-DC converter so that more energy can actually be used for the DC House.

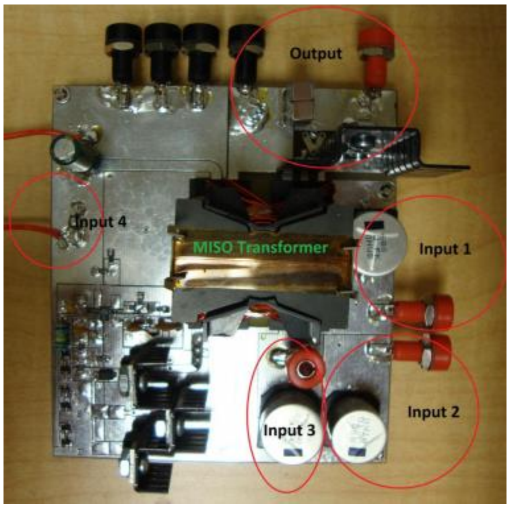


Fig. 4. First prototype of MISO Converter.

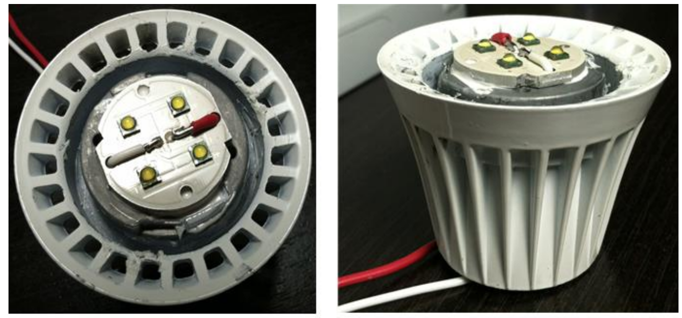
C. DC Distribution

Moving further to the right in Figure 1 is the main DC bus with the rest of DC distribution system. Since AC electrical system is the predominant electrical system used to distribute electricity, a DC House is designed to allow easy adoptability in its implementation. If a house has been constructed to operate with AC system, then transforming to DC should be a relatively easy transition. In particular, the move to the DC system should incorporate the use of the same AC wiring system and lighting fixtures. This not only minimizes the cost of implementing DC House, but also promotes sustainability by reusing common AC house electrical components.

D. DC Loads

Finally, at the end of the DC distribution system are the loads of the DC House. For rural areas in third world countries, the main residential load is predominantly lighting. Small refrigerator may also be needed for medicines in a health clinic. Due to advances in LED technology, it is now possible to have DC light bulbs that are energy efficient and low-cost. Such DC light bulb is currently being developed for the DC House project which can operate straight from 48 V DC and uses the same Edison screw base as shown in Figure 5. The development of the 48 V DC light bulb is deemed necessary since currently there is no commercially available low power 48 V DC LED light bulb.

Other loads in the DC House currently consist of commercially available devices and appliances used for outdoor activities such as camping as well as those used in recreational vehicles (RV). At present, in addition to DC light bulb the DC House prototype at Cal Poly has several DC loads for testing purpose including crockpot, fan, television, radio, and small refrigerator. To operate these loads to the main 48 V DC bus, DC wall plug will be necessary. Currently a smart DC wall plug is also being developed to enable a universal connection from a 48 V DC bus to any DC load required by a load; thus providing a simple and easy connection between DC loads and DC bus.



(a) (b)

Fig. 5. First prototype of DC Light bulb.

E. DC System Protection

For safe operation of the DC House, protection devices will be required for the DC House. These devices vary from fuses and breakers located in several points on the DC House distribution system. In addition, a low-voltage DC arc-fault interrupter is currently being developed with funding provided by the California Energy Commission.

V. COST

Cost of a DC House system will vary based on how many sources and loads are being used by the house. Also as previously mentioned, the DC House project offers the family or individual based alternative to rural electrification, and as such its implementation can start with as simple as having a DC light bulb for a family. Therefore the cost of implementing a DC system may start from as low as the cost of a portable light bulb which is approximately \$50. However, as the DC system grows bigger, its cost will increase proportionally with the level of power. For a 150 W house, the cost has been estimated to be between \$750 and \$1000.

VI. RECENT STATUS AND FUTURE PLANS

Figure 6 shows the DC House prototype currently being constructed on Cal Poly's campus. The house is made out of a 8'x10'x7'10" commercially available shed. On the roof sits a 250W roof-top solar panel donated by San Diego Gas & Electric to power the house. Additional energy source for the house comes from two wind/hydro power simulators each capable of producing as much as 75W (Figure 7). Inside the house, various DC loads with DC wall plugs will be incorporated as previously explained. The completion of a fully functional DC House is planned by the end of 2014.

Future plans for the DC House project include field testing and implementation in several locations in Indonesia and in Philippines through the support from local universities, government, and industry. At present, three locations in and around Java Island have been identified: Bandung – West Java, Malang – East Java, and Madura Island. For each location, a 250 to 300 W DC House will be constructed to show case its feasibility as an alternative solution for rural electrification. Ongoing efforts focusing on getting more field testing locations primarily throughout the Indonesian archipelago are currently being conducted.

Fig. 6. First prototype of Cal Poly's DC House.

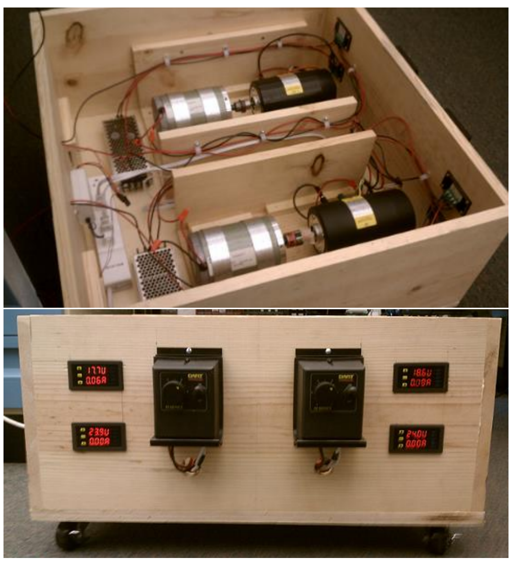


Fig. 7. Hydro and Wind Power simulator.

Another future plan for the DC House project is to expand its system to include a network of DC Houses within a geographically small area. A study showing the feasibility of a DC distribution network consisting of 25 DC houses has been conducted as depicted in Figure 8. The expansion of the DC House is intended to connect multiple individual DC Houses wherein each can still function independently without the others. However, the option or ability to connect to other DC Houses in the small vicinity will help in a more reliable operation since its electricity may come from any neighboring house. This approach will be most suitable and beneficial for places where a family or a clan living in a cluster of houses next to each other.

Another long term plan for the DC House project is to extend its functionality as a disaster relief house to aid people in areas hit by natural disaster such hurricane, tornado, earthquake, etc. The DC House will be scaled down but also redesigned such that it will require minimum storage space as well as short construction time. The disaster relief house will still operate from renewable energy and/or human-powered sources with some components integrated or embedded within the house.

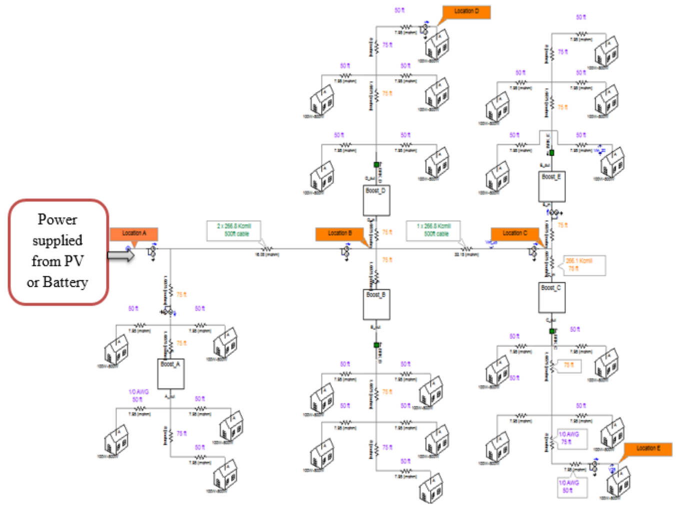


Fig. 8. DC Network system.

VII. CONCLUSIONS

The development of a DC House system with its main components is presented in this paper. The project is a humanitarian effort aimed to promote the use of renewable energy sources for rural electrification mainly in developing countries. The project has long and short term goals with a working prototype planned to be completed by the end of 2014. Following this, field implementations will be conducted in 2015 at several locations in Indonesia and Philippines. Many technical difficulties have been encountered during the development phase; however, the real challenge will be when field implementation of the DC House is taking place.

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