A decision-making framework to optimize roof functionality in the design of sustainable buildings

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ABSTRACT: The decisions made in early design stages contribute greatly to the energy performance of a building in various aspects. The roof, as part of the envelope, is one of the most significant factors in the development of sustainable buildings, however, there is a lack of integrated roof design guidance to better inform architects and building practitioners. Therefore, a rational and lucid approach that manages tradeoffs in order to achieve optimal solutions to designing and developing a more energy efficient and sustainable roof is imperative. Applying the framework, the roof area can be better applied for various purposes during different energy design and sustainable development stages. This research encompasses the method used to develop a roof design assistant framework or "RoofConsultant" that can be utilized to optimize roof functionality in design and development of sustainable buildings. In the course of the literature review and research process, a comprehensive knowledge and information database is developed and categorized based on seven key roof functions. Appropriate strategies within these functions are addressed with regard to eight US climate zones. Energy codes, standards, and guidelines are used to develop boundaries for the application of roof design strategies in different climates and locations. Through this comprehensive approach, RoofConsultant aims to be an interactive tool for designers that can lead to more effective sustainable development of roofs.

KEYWORDS: Roof Design, Integrated Roof, Sustainable Building, Net Zero Energy Building, Energy Efficiency

INTRODUCTION

Major design decisions regarding building sustainability are made primarily by architects and designers in the early design stages. Changing design parameters like form, orientation, and envelope configuration leads to buildings of higher quality design that can use around 40% less energy than a lower quality design (Wang, 2006). In the building envelope, the roof is particularly an important area in the conceptual stage of building design. Various roof design strategies have been developed to improve energy efficiency of buildings, generate energy, and increase water retention and waterproofing capability.

Currently, there are few useful tools or programs that help design sustainable roofs. Some programs can provide designers and consultants with valuable information in practices. Three programs (Climate Consultant, RoofNav, and RoofPoint) are frequently used by building practitioners to analyze various aspects in roof design. Each of the three has its target areas of analysis.

Climate Consultant, developed by UCLA (Milne 2007), graphically presents climate information (including temperature, humidity, solar radiation, and others such as wind and precipitation), along with guidelines and strategies for climate-based design decisions in specific locations. It is not specifically used for roof projects. RoofNav is a large materials database that provides roof professionals with Factory Mutual (FM) certified material options and step-by-step guidance on how to identify, configure, and install different roofing assemblies and components that comply with FM roofing standards.

RoofPoint (CEIR 2012) rates roof performance in terms of energy efficiency and renewable energy generation. It uses a calculator whose primary function is to measure the energy and environmental characteristics of roofing systems in commercial and institutional buildings and compare different roof system solutions with regard to energy and environmental impacts (Hoff and Resort 2013). RoofPoint is a rating tool that focuses on end results and practices; it uses five functional areas of the roof, and provides 23 total sustainable strategies. Quantitative outcomes provide results in benchmarking for better practices in energy efficiency and renewable energy systems applications.

A new tool, RoofConsultant, is proposed in this paper. It focuses on design aspects different from the information that existing programs like Green Building Studio, Vasari, or Ecotect can provide; these tools use quantitative analysis in building energy calculations or simulations. RoofConsultant uses a qualitative approach for making efficient design decisions, providing options and sustainable measures for designers and architects to consider.

The target area of RoofConsultant, as mentioned, is on early design phases. Designers do not usually pay much attention to the roof area in the design process, but it has a significant role in developing sustainable buildings, or achieving Net Zero Energy Buildings (NZEBs). RoofConsultant aims to provide design strategies that can help achieve goals of energy efficiency and renewable energy generation, resulting in more sustainable buildings. The following section discusses the methodology of RoofConsultant and the contents.

1.0 METHODOLOGY

A compendium of strategies (or database of roof design strategies) is the basis to developing an interactive tool (RoofConsultant) that will be customized to give useful information for the user to make decisions for the design of sustainable roofs.

1.1. Framework

RoofConsultant is organized into three primary areas (i.e., roof functions, boundaries, and reality) representing the most important principles. Each of the three conceptual groups includes the contents as follows.

1. Roof Functions: key design parameters or sustainable strategies that should be considered in the early design phases.
2. Boundaries: specific code requirements and guidelines for particular climate conditions.
3. Reality: overarching concerns that need to be thought out since there are always issues about aesthetics (roof shape), implementation costs, and/or psychological aspects in a built environment (Fig. 1).

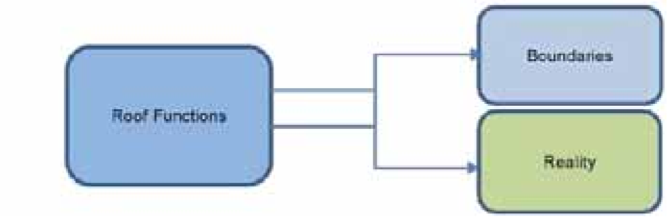

Figure 1: Three conceptual areas of RoofConsultant framework. Source: (Author 2015)

Roof functions

In order to recognize different energy and environmental outcomes, 15 strategies have been identified to have the most influence, based on the literature review. These systems are categorized in seven comprehensive functional areas, which were investigated in detail to develop specific design strategies: Energy efficiency, Energy generation, Daylighting, Equipment allocation, Rainwater collection, Waterproofing, and Recreation. The first three functional categories deal with energy issues more closely than the other four categories.

1.2.1. Energy efficiency

The roof has much potential for increasing the efficiency of energy use in a building system. This function addresses roof design strategies as a key influencer of building energy efficiency. The energy efficiency function consists of four strategies which have substantial impact on the energy use of buildings; these are green roof, cool roof, thermal insulation and thermal mass.

Green roof: Green roofs are considered to be effective strategies in energy efficiency design, and specifically appropriate for both winter heating energy reduction and summer cooling energy reduction. A green roof can improve stormwater management capability and urban air quality, and aid in reduction of the urban heat island effect, while also providing habitat for wildlife, and aesthetic appeal. Additionally, green roofs can extend roof life, improve acoustics, and enhance architectural interest and biodiversity (Dvorak and Volder 2010; Köhler et al. 2002; Niachou et al. 2001; Oberndorfer et al. 2007; Sailor 2008; Castleton et al. 2010).

Many studies have been conducted to investigate the potential building energy savings of green roofs.

Some researchers investigated selecting efficient vegetated roofing systems for different climate conditions (Grant & Jones 2008). Alexandri and Jones developed a model to estimate the potential of reducing temperatures in nine cities by applying green roofs (Alexandri and Jones 2008). Other studies have investigated microclimate impact of vegetation cover (not specifically green roof) up to a 1.3 oC reduction in a city's maximum temperature (Sailor 1995).

Cool Roof: A cool roof's first and foremost benefit is energy efficiency in building systems. By reducing the roof surface temperature, cooling loads are reduced, which gives energy and cost savings and reduced electrical grid strain from the reduction of peak cooling demands. Resultantly, cool roofs result in better air quality, reductions in carbon and power plant emissions, and mitigation of urban heat islands. Cool roofs also increase roof life and occupant comfort, and are easily implemented (Akbari et al. 2004, 2008; Berkeley Lab 2014; Bhatia et al. 2011; Bozonnet et al. 2011; Santamouris et al. 2011; Synnefa et al. 2007; Van Tijen and Cohen 2008).

Energy savings from using reflective materials to decrease temperatures have been investigated through actual measurements and simulation programs. Jo et al. reported that cool roof technology can result in building electricity consumption reduction of 1.5%-1.8% and 2.8%-3.4% using a 50% and 100% cool roof (Jo et al. 2010).

Thermal insulation: Thermal insulation can reduce the rate of heat transfer through conduction, convection, and radiation. It prevents heat from exiting or entering a space, keeping it at a more constant temperature, and gives energy savings, economic benefits, and environmental profits. Thermal insulation in roofing systems is an important factor in determining the thermal performance of buildings due to the direct exposure to radiation and outside environments (Al-Homoud and Mohammad 2005; Al-Jabri et al. 2005).

Thermal mass: Thermal mass is a property that enables materials to absorb and store thermal energy, and delay heat transfer from outdoor to indoor space or vice versa, and is significant in determining thermal performance of building envelopes, including roof surfaces. Thermal mass works well in commercial buildings by shifting peak summer loads to later in the day, closer to closing times. Energy demand is moved to an off-peak period, and peak temperatures, peak loads, and emissions are reduced (Baggs and Mortensen 2006; Kalogirou et al. 2002; Shaviv et al. 2001).

1.2.2. Energy generation

Energy generation systems can often be placed on the roof. An appropriate energy generation system can alleviate energy use and costs significantly. This function addresses the roof design as a key influencer of energy generation in buildings. Energy generation as a function in buildings consists of four strategies: solar power (PV systems), solar thermal, wind power, and biomass & bioelectricity.

Solar power: Solar photovoltaic systems convert light from the sun directly into electricity and generate pollution-free energy. They can be installed on the roof as well as on the wall of commercial buildings as a grid-connected photovoltaic (PV) application (Parida et al. 2011). Solar PV systems are commercially available and can be reliably effective depending on the climate zone of interest. Often, times of year with high cooling demands coincide with high available solar energy, which highlights the potential utility of this technology.

Solar thermal: Solar thermal systems use thermal energy to heat up water or air. This thermal energy can be used for various applications including providing hot water, heating and cooling of buildings and spaces, and generation of electric power (Kalogirou 2004).

Wind Power: Wind turbines hold potential to produce low-cost energy on the roof (Abohela et al. 2013). Wind energy is a green, indigenous power source that is permanently available, and can be stored when winds are low. Its cost is generally limited to installation of the wind turbine, and it can be a great resource in remote locations, such as in the mountains. This technology will play an important role in future energy generation, due to its technological maturity, good infrastructure, and relative cost competitiveness (Harbert et al. 2007; Mithraratne 2009).

Biomass & Bioelectricity: Biomass is biological material derived from living, or recently living organisms, from which heat energy is derived. Biomass is a promising renewable energy source as it can provide energy security in regions with a lack of fossil fuels, while also reducing the carbon emission level per unit of energy delivered (Field et al. 2008).

Bioelectricity is the generation of electric power potential or current produced by or within living organisms. Bioelectricity can be harnessed for power through plant-microbial fuel cells2, (PMFCs), a new technology. PMFCs can also be developed to treat waste water and monitor pollutants (Deng et al. 2012).

1.2.3. Daylighting

Daylighting in buildings can significantly improve lighting quality. Proper sizing and design with suitable lighting control can save energy, by optimizing the size of apertures to control both illuminance level and annual energy performance (Heschong and McHugh 2000; Johnson et al. 1984). This function is categorized in three top lighting system examples: skylights, light pipes, and saw-tooth and roof monitors.

1.2.4. Equipment allocation

Roof areas in commercial buildings are frequently used to house HVAC systems such as Rooftop Air Handling Units (AHUs) and cooling towers. Placing the system on the roof results in less visibility than in other parts of the building, and placing loud equipment on the roof reduces volume at ground level.

1.2.5. Rain water collection

The rainwater collection function is included as water conservation issues become more important and prevalent in current times. Roofs comprise a significant percentage of impermeable areas, yielding substantial potential for rainwater collection. The application of an appropriate rainwater harvesting technology can utilize the rainwater as a valuable and necessary water resource (Villarreal and Dixon 2005).

1.2.6. Waterproofing

The waterproofing of the roof is of great concern in the roofing industries. An appropriate water roofing system can protect structure and interior content, extend structure lifetime, provide thermal comfort, and improve environmental quality by preventing mold. Roof coatings that meet energy requirements give additional benefits of cool roofing and air conditioning savings. Cooled roofs also do not experience temperature change stresses, giving reduced future maintenance due to thermal shock (NYC Environmental Protection 2012).

1.2.7. Recreation

Roofs can be used as a myriad of recreational spaces (plant roof, vegetation production, rooftop farming, restaurant, pool, etc). Physical characteristics of the roof surface, including slope, materials, and loading capacity, must be considered when designing for recreation. The benefits of many different kinds of roof functions can be reaped when designed intelligently.

1.3. Boundaries

The roof functions in the seven areas discussed are dependent upon certain circumstances such as different climate conditions and standards. This section presents important conditions that need to be considered at the time of roof design. While not all referenced sets of standards are dedicated to roof design, they contain useful information.

1.3.1. Climate Condition

The climate condition in which a building is situated is the one of the most important parameters to consider in efficient roof design. Code and standard requirements vary by climate region. According to IECC 2012, the US climate zones are divided into eight temperature oriented areas. USDOE’s Pacific Northwest National Laboratory (PNNL) identified sixteen representative cities in these areas. The sixteen cities were used here to specifically develop design strategies that work suitably for each location (Table 1).

Table 1: 16 cities of different climate zone in US. Source: (IECC 2012)

Climate Zone	Representative City
1A	Miami, Florida
2A	Houston, Texas
2B	Phoenix, Arizona
3A	Atlanta, Georgia
3B-Coast	Los Angeles, California
3B	Las Vegas, Nevada
3C	San Francisco, California
4A	Baltimore, Maryland
4B	Albuquerque, New Mexico
4C	Seattle, Washington
5A	Chicago, Illinois
5B	Boulder, Colorado
6A	Minneapolis, Minnesota
6B	Helena, Montana
7	Duluth, Minnesota
8	Fairbanks, Alaska

1.3.2. Codes, standards, and guidelines

Building codes, standards, and guidelines help building practitioners design and develop sustainable buildings. These documents were used in this study to provide important guides for the design of roof.

1. IECC-2012 (International Energy Conservation Code). This code is relevant to addressing the design of energy-efficient building envelopes, and the installation of energy efficient systems. Performance of materials and systems is emphasized.
2. ASHRAE Standard 90.1-2010 (American Society of Heating and Air-Conditioning Engineers). Standard 90.1 describes the minimum requirements for energy-efficient design in most buildings besides low-rise residential buildings, and covers system requirements in new and existing buildings. It is especially useful for engineers, and building system designers.
3. IgCC-2012 (International green Construction Code). The IgCC is the first model code that includes sustainability measures for the entire construction project, as well as its site, all the way from early design states to beyond certificate of occupancy. This code addresses holistic sustainability through energy efficiency, waste reduction, and healthy and community welfare.
4. ASHRAE AEDG 50% (Advanced Energy Design Guides). The Advanced Energy Design Guides offer recommendations for achieving 50% energy savings based on the minimum requirements outlined in Standard 90.1-2004. The Advanced Energy Design Guides offer steps to ultimately help achieve a net zero energy building.
5. ASHRAE Handbook fundamentals, 2009. This Handbook addresses basic principles and data pertinent to the HVAC&R industry.

1.3.3. Benchmarking

As mentioned earlier, there are some existing tools that can be used in benchmarking such as Climate Consultant, RoofPoint, and RoofNav. Additionally, the EIA's Commercial Building Energy Consumption Survey (CBECS) report was also referenced to show the typical energy consumption levels for different building types with the metric Energy Use Intensity (EUI).
Figure 2 shows the framework of RoofConsultant. This is an expanded version of Figure 1. The right column represent different roof functions and the left column represents the boundaries and reality aspects of each function. Each function on the right is related to the boundaries and reality section in the left column (Fig 2).

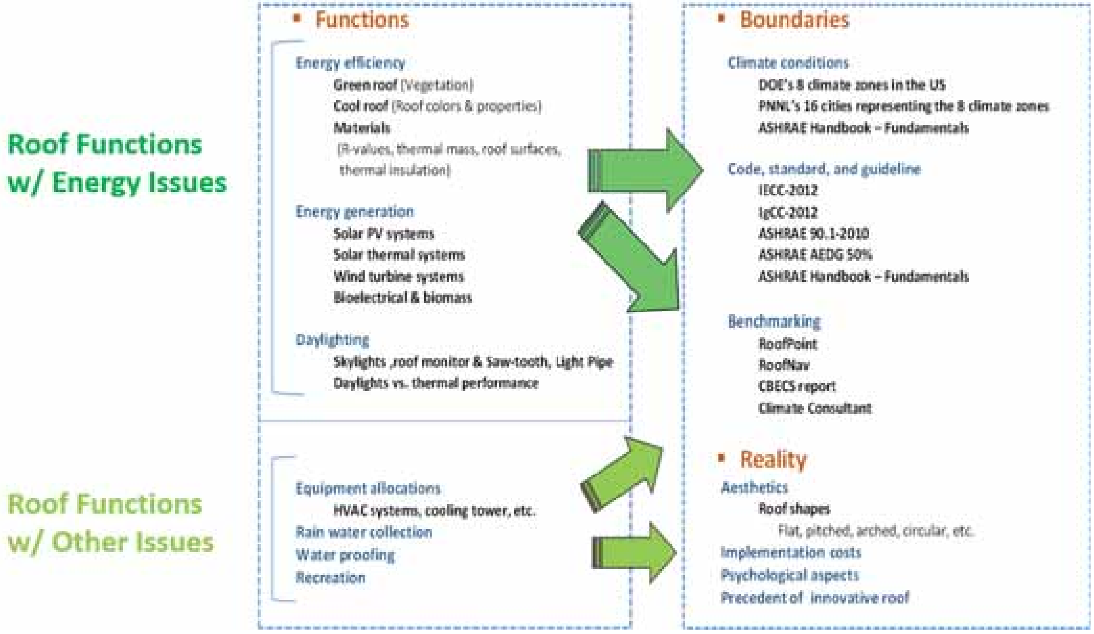

Figure 2: Framework of RoofConsultant. Source: (Author 2015)

1.4. Reality

The functions and boundaries have been determined in the framework; however, there are still important aspects that must be considered in the design process, known as reality. These are aesthetics (i.e., roof shapes), implementation costs, and potential psychological characteristics. These comprise the third of the three structural areas in the RoofConsultant framework.

2.0. COMPENDIUM OF STRATEGIES

After developing the compendium of strategies, a database is organized in an Excel spreadsheet. The information included in the spreadsheet is used as the information and data sources of the RoofConsultant tool (Fig 3).

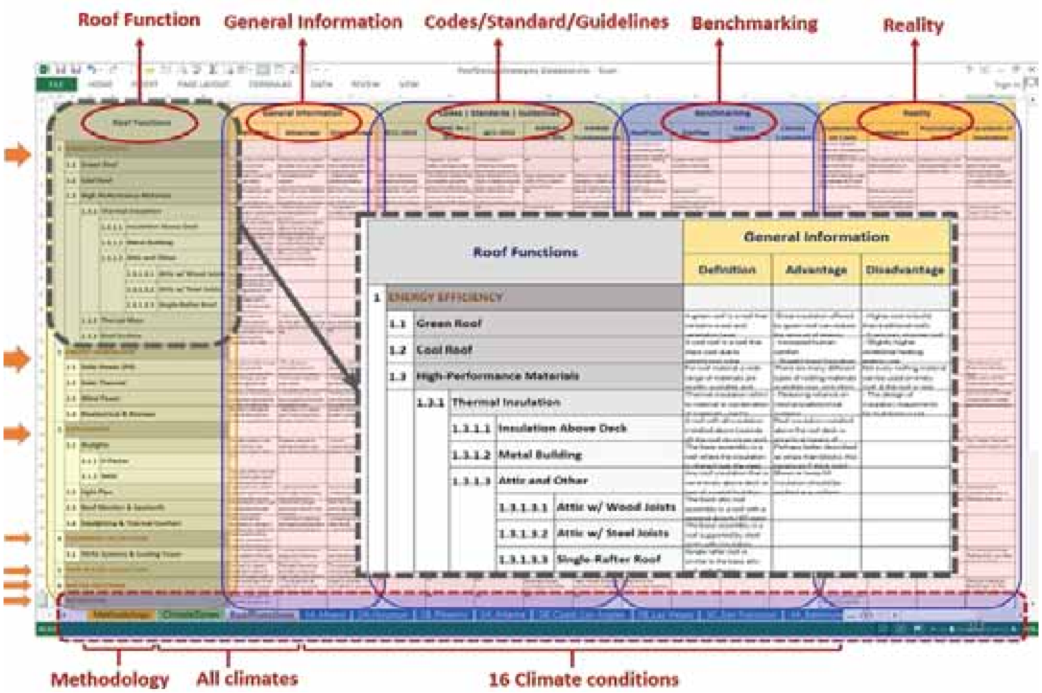

Figure 3: Compendium of strategies.

Each column corresponds with a discussed area of the framework. From left to right, column categories address roof functions, general information, codes and standards, benchmarking, and information relevant to the reality of implementation. The same structure is repeated for each of the 16 representative cities discussed above. Figure 4 shows a snap shot of the 16-category spreadsheet that includes individual roof design strategies for each city (explained in Figure 3.)

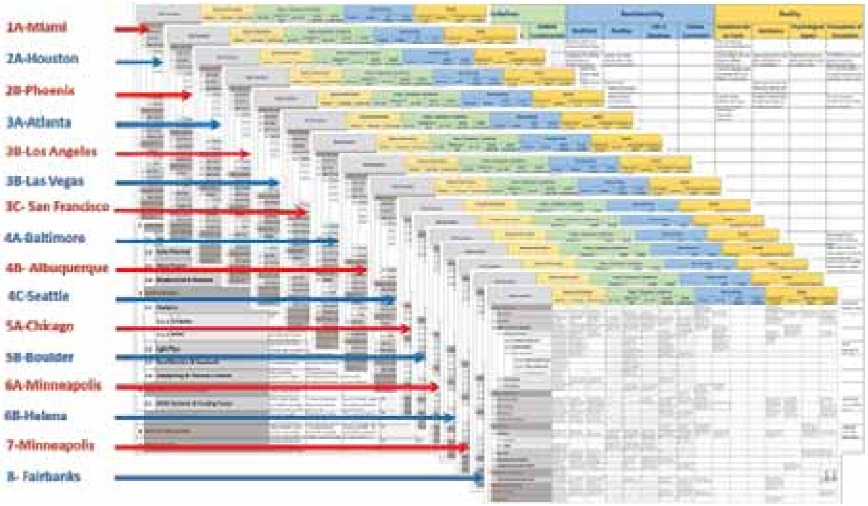

Figure 4: Roof design strategies for 16 different cities.

3.0. TOOL DEVELOPMENT

In order to better understand and use the provided information, we developed the tool. RoofConsultant uses an easy and affordable framework that can effectively help practitioners design roofing projects based on climate conditions. The tool development structure is presented in Figure 5. Python programming language is used for controllers of the framework. JavaScript and jQuery UI are used for interactive functionalities.

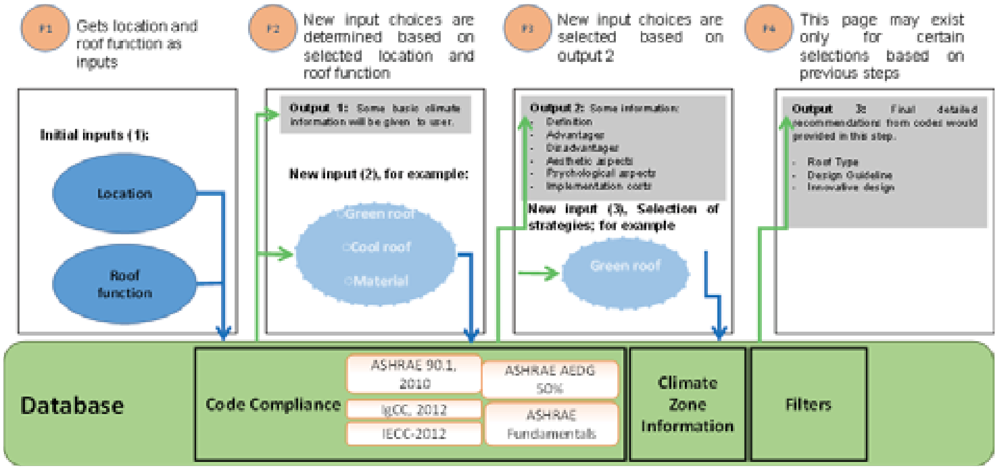

Figure 5: Tool development structure.

The user first inputs location and desired roof function, which dictate input choices to follow. The user can then select roof functions based on information outlining definitions, advantages, and disadvantages.. After selecting a roof function, the user is provided information for implementation through codes, standards, benchmarking and reality aspects.

CONCLUSION

This paper presents the importance of effectively utilizing the roof area to achieve the goals of the 2030 Challenge or Carbon-Neutral by 2030. Seven key roof functions are evaluated for different climate zones in the US based on existing codes, standards and benchmarking. An information database was developed for the improvement of sustainable commercial roof design. This framework would be the basis to illustrate the potential value of each strategy in specific locations for future calculation. Next steps include further development of a number-based metric, which will be based on numerous simulations. Pre-simulated performance data will be used to provide quantitative, comparative guides to the users. Simulation technologies such as EnergyPlus, Radiance, OpenStudio etc., and field measurements will assist us in this analysis.

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ENDNOTES

1 FM approvals certification assures customers a product or service that has been objectively tested and conforms to the highest national and international standards.

2 Plant-Microbial Fuel Cell generates electricity from organic matter excreted from the roots of living plants.