Analysis of low-energy envelope and lighting measures for single-family dwellings in the West Indies

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ABSTRACT: Most island nations of the West Indies rely predominantly on imported petroleum oil to meet their energy needs despite their strategic location to an abundance of renewable energy resources, which has contributed to significantly high electricity tariff in the islands. Meanwhile, buildings in the West Indies consume over 70% of the electricity generated in the islands. However, sparse information is available for architects, engineers, and homeowners about the efficient design and use of energy in buildings. Appropriate environmental design and construction such as passive and low energy design strategies which can be employed in the region are often neglected. Therefore, this paper presents the preliminary results from an analysis of the energy savings potential in single-family residential buildings in the islands by adopting several low-energy measures. The analysis was performed using eQuest 3.65 building energy simulation software. The ASHRAE Standard 55-2013 thermal comfort adaptive standard (ASHRAE 2013a) was used for the analysis of modeled thermal environments.

This study first developed baseline energy models that represent typical single-family residential buildings in the islands. To develop representative baseline residential models in the region, this study collected single-family housing data from home developers of the areas and performed interviews. The representative occupancy and operation scenarios in the islands were developed based on population statistics available in the island nations. The modeled energy consumption of base-case buildings are also compared against a previous study on residential building energy use in the region. Several energy conservation measures were then applied to the base-case models. These include measures for building orientation, envelope and fenestration, lighting, and equipment. Finally, this study developed recommendations for architects, engineers and homeowners in this region who wish to construct low energy residential buildings so as to avoid the needs for detailed analyses on every occasion when planning single-family residential buildings.

KEYWORDS: Low Energy Measures, Building Energy Simulation, West Indies, Energy Conservation Measures

INTRODUCTION

Most island nations of the West Indies rely predominantly on imported petroleum oil to meet their energy needs despite their strategic location to an abundance of renewable energy resources, which has contributed to significantly high electricity tariff in the islands. A report prepared for Caribbean Renewable Energy Capacity Support Project (CRECS) project stated that the cost for electricity for domestic use in Caribbean Community (CARICOM) states is among the highest in the world (Gardner 2011; Yepez-Garcia et al 2010).

Buildings in the West Indies consume over 70% of the electricity generated in the islands. The impact from climate change and increasing energy costs on small islands are now forcing building owners and operators to make changes and pursue sustainable development methods (Mimura et al 2007; UNEP 2010). Many of these owners are already aware that adaptation of more passive design techniques and low energy technologies will generate valuable co-benefits important to them, namely, short-term energy savings and long-term lifecycle cost reductions (Stern 2007). However, sparse information is available for architects, engineers, and homeowners about the efficient design and use of energy in buildings.

In recent years many single family dwellings that are constructed in the West Indies, have moved away from the traditional housing techniques, such as ventilated hipped or gabled roof, long roof overhang, high vaulted ceilings and open-design walls and have adopted a home design which require the use of mechanical equipment such as air-conditioning units. Hence it is now common to find many current single-family homes relying on the use of these costly systems for thermal comfort. However, these active systems demand high energy consumption. Meanwhile, appropriate environmental design and construction such as low energy envelope and lighting measures which can be employed in the region are often neglected.

Therefore, the purpose of this study is to identify and examine the potential energy performance benefits by applying low-energy principles appropriate for the average residential owner in this region. To accomplish this, the following objectives were considered:

1. Develop a base case that represents a typical single-family dwelling characteristics in West Indies.
2. Simulate and analyze the energy performance of the developed base-case single-family residential models.
3. Simulate and analyze the potential energy savings from the selected low energy envelope and lighting measures by applying them to the base-case models.

1.0 METHODOLOGY

The procedures used to determine the low energy envelope and lighting measures appropriate for the island states of this region is outlined in the following three phases. *Phase I Research* involved the collection of background materials needed to develop a base-case single-family residential model for the islands. To develop representative baseline residential models in the region, this study collected single-family housing data from home developers of the areas and performed interviews. Housing construction materials on these islands which consist of concrete, masonry and metal are preferred because of their durability in this climate. Roofing material of standing seam or concrete roof tiles, aluminum and metal windows and door frames are all materials resistant to the weather and termites. The ASHRAE Handbook Fundamental 2013 (ASHARE 2013b) was referenced to assign appropriate thermal characteristics of the materials. Manufacturers' specifications of the typical household equipment and appliances used in this region provided information of energy and plug loads for the base-case models (TTEC 2014).

For the occupancy, lighting, and DHW schedules, the National Renewable Energy Laboratory (NREL) Building America House Simulation Protocols (NREL 2010) was used as reference. Several modifications were applied to the daily occupancy and equipment usage profiles. These modifications were based on the CARICOM Census report (CARICOM 2009) that defined the predominant average West Indian household size as the five persons' household. The report also provided information about the structure of the five persons' household which may consist of young children, teenagers, elderly and working adults with weekday normal working hours of 7AM to 4PM. The cooling set-point temperatures were selected to comply with the acceptability limits of ASHRAE Standard 55-2013 adaptive thermal comfort provision (ASHRAE 2013a) for this hot-humid tropical region.

Phase II Research performed the energy modeling and simulation of the base-case residential models developed using the information collected during the Phase I research. This included a determination of the annual energy consumption and thermal comfort. The base-case models have similar configuration and area, however one is designed with on-grade slab and the other with elevated slab. The International Weather for Energy Calculations (IWEC) hourly weather data for the island of Martinique was selected to perform the energy modeling calculations for this group of islands. The modeled energy consumption of base-case buildings were also compared against a previous study performed for similar residences in a neighboring region (Holmes and Kao (2010)).

Phase III Research explored and selected eight individual energy conservation measures (ECM) to optimize the energy performance of base-case single-family residential models. To select energy conservation measures (ECMs) appropriate for the region, this study reviewed recommendations of low energy envelope and lighting measures taken from analyses and case studies and guidebooks produced by the NREL technical information program (NREL 1994), Building America Best Practices Series (PNNL 2011) a technical handbook on Passive and Low Energy design published by the Commonwealth Secretariat (Baker 1987), the International Energy Conservation Code (IECC) 2012 (IRC 2012). Finally, this study combined and re-simulated the proposed individual measures as a group to maximize potential savings.

1.1. Geography and climate information of the West Indies

The Islands of the West Indies are located between latitudes 23° and 10° north of the equator. This chain of islands extends south from the Florida peninsula, curving 4,020 kilometers (2,498 miles) to the northeast coastline of South America. The West Indies archipelago separates the Caribbean Sea from the Atlantic Ocean. The archipelago is geographically divided into three groups. The focus of this study included all of the islands of the group known as the Lesser Antilles and the island of Jamaica, as shonw in Figure 1. The Lesser Antilles is made up of a large arch of twenty one smaller islands, and is located in the south and southeast between latitude 10°N and 18°N of the equator.

The seasonal climate of the West Indies varies slightly from island to island. The different topography, size and orientation help to create local micro-climates for each island. In general however, there is a high rate of sunshine with very little daily or yearly variation throughout the entire West Indies. The trade winds blow throughout the year from the northeast, and are warm and moist (Taylor 2005). Generally, the temperature ranges from 23°C to 25°C (73.4°F to 77.0°F) in January and from 25°C to 31°C (77.0°F to 88.0°F) in July with small difference between islands (Wilson 2014).

Figure 1: Study area and the location of Martinique Island of which hourly weather file was selected for the analysis. (Source: Map from http://city-data.com)

2.0 BASE-CASE BUILDING DESCRIPTION

The base-case residential simulation models developed in this study are simple rectangular or square shaped plans with a 123.9 m^2 (1,334 ft^2) of floor area. Table 1 summarizes the characteristics of the base-case single-family residential model used in the eQuest simulation tool in this study. Figure 2 shows the shape and geometry of the base-case model as well as a photo of a typical contemporary single-family residential building in the West Indies. The single story structures are constructed of either slab on grade or with slab elevated on concrete piers construction. The layout consists of three bedrooms, dining room, living room, kitchen and two bathrooms. The selected construction materials consist of 152.4 mm (0.5 ft.) concrete masonry blocks, 28 ga galvanized standing-seam metal roof with 609.6 mm (2 ft.) overhang, single pane casement aluminum windows. Household equipment and appliances included domestic water heater (DHW), kitchen and living room appliances. Wilson (2014) presents occupancy, lighting, and DHW schedules used in this study for the two separate zones: Living Room zone and Bedroom Zone.

Table 1: Base-case building description.

BUILDING CHARACTERISTICS	BASE CASE BUILDING DESCRIPTIONS	BASE CASE SIMULATION INPUT	INFORMATION SOURCE
ARCHITECTURAL			
Building Type	Single Family, detached dwelling-Slab on Grade		
Climate Zone	Zone 1A (IECC 2009)		
Gross Area	1,334 s.f.		
Floor Plan	3 Bedrooms Dwelling, Total 2 Zones	Living Area: 506.9 s.f.; Bedrm.: 707.2 s.f.	
Floor to floor Height (ft)	10 ft.		
Orientation	South facing		
CONSTRUCTION			
Wall Construction	Enclosure walls: 6" CMU with cement plaster finish both sides	Assembly U: 0.513	ASHRAE 2013b
Floor construction	4" concrete slab, tile paver finish	Assembly U : 5.56	ASHRAE 2013b
Roofing/Attic Construction	28 ga. Aluminum sheeting over radiant barrier sheets, vented attic	Assembly U: 0.73	ASHRAE 2013b
Window Construction	Single-pane glazing, aluminum frame no thermal break	U-factor: 1.30 SHGC :0.66	ASHRAE 2013b
Window Area		Living Area: 10% WWR Bedrm.: 12% WWR	
Infiltration	Estimated Infiltration for small buildings	0.48	ASHRAE 2001
MECHANICAL SYSTEM			
HVAC System	Direct Expansion- Unitary Split System per zone	36,000 Btu unit, SEER = 16	
DHW	30 gallon Water Heater Electrical powered	Capacity= 30 gals. EF: 0.93	
SPACE CONDITIONS			
Space Cooling Setpoint	ASHRAE 55-2013 for Naturally Ventilated Buildings	80F (Occupied)	ASHRAE 2013a
Lighting	Incandescent lights	Living Area.: 1.2 W/s.f.c Bedrm.: 1.0 W/s.f.	Wilson 2014
Electrical Equipment	Home appliances and plug loads	Living Area: 1.0 W/sf Bedrm.: 0.2 W/sf	Wilson 2014

Figure 2: Typical contemporary single-family residential building in the West Indies (Left); and shape and geometry of the base-case model with a slab-on-grade configuration (Right).

The mechanical system which provides only cooling, consists of two split system air-conditioning (AC) units, located one each in the Living Room and Bedroom zones. The AC units were scheduled to be available only when the zones were occupied. The cooling set-points selected for the initial base-case analysis is 80°F which is within the acceptable thermal comfort range of ASHRAE Standard 55-2013 for natural ventilated (NV) buildings in hot-humid climates. The zones was modeled to be naturally ventilated when natural ventilation can provide enough cooling to keep the zone temperature below 80°F, and the zone was occupied. The DWH system selected was a 30 gallon, electrically-powered equipment, with an efficiency determined from the manufacture specifications. The average daily hot water consumption of 162.8 L/day (43 gallons /day) was determined by the 2012 IECC hot water equation (IRC 2012).

3.0 ENERGY CONSERVATION MEASURES (ECMS)

The main strategy for low energy building design for these islands is to reduce solar radiation throughout the year. The selection of low energy components for the building enclosure that aid in reducing solar heat gain made up the majority of the eight individual energy conservation measures that were selected. Seven of the measures involved building components directly affecting the enclosure. The other two measures consisted of interior lighting and landscape shading. The simulation for preliminary analysis of each energy conservation measure was conducted using the eQUEST 3.65 program tool. The description of each measure is provided in the following sections.

- *ECM 1 Increased roof insulation*: This measure added rigid polystyrene insulation to accomplish a cumulative value of R-30 to comply with the requirements of the 2012 IECC for roofing assembly. In this case, the rigid insulation was applied above the ceiling to seal from the vented attic area.
- *ECM 2 Radiant barrier at ceiling:* This measure added radiant barrier at ceiling surface or the attic floor to re-radiate heat energy in the roof attic back towards the roof. The radiative heat which is also transmitted by the roof surface across the attic cavity can be minimized by reducing the emissivity of the underside of the roof covering or by increasing the reflectance of the cool inner surface of the ceiling.
- *ECM 3 Exterior wall insulation:* This measure added insulation to exterior wall enclosure adequate to achieve the R-value of 4.This is in compliance with 2012 IECC guide for homes in climate zone 1. This can be a combination of granular perlite poured in or blown through a nozzle into the masonry block cavity. Also, rigid insulation board may be applied over interior wall surface and furred with gypsum wallboard, U value 0.25 for the finish material.
- *ECM 4 Improved glazing:* This measure added efficient windows with double pane, low-e glazing. To comply with 2012 IECC guide for homes in Climate Zone 1, efficient windows should include low emissivity with solar heat gain coefficient (SHGC) value of 0.25.
- *ECM 5 Improved window frame:* To improve the efficiency of aluminum frames to control heat conduction, this measure changed the frame material to steel frame with thermal break for a U-factor (heat loss rate) of 2.856W/m^2-°C (0.503 Btu/h-ft^2-°F).
- *ECM 6 Window overhang*: Window design guide by the Efficient Windows Collaborative (EWC) in association with the University of Minnesota provided information on window shading strategy (EWC 2014). Exterior overhangs have the advantage of reducing solar heat gain without diminishing the view. The guide sun angle calculator computed 304.8 mm (1 ft.) or greater overhang on all windows to provide shade for window glazing in this region where the sun’s angle remains high in the sky throughout the year. This measure tested both one foot 304.8 mm (1 ft.) and 457.2 mm (1.5 ft.) window overhangs, and applied the 457.2 mm (1.5 ft.) to windows in the west and east facades.
- *ECM 7 Compact Fluorescent Lighting Power:* This measure replaced existing incandescent lamps with compact fluorescent lights (CFL). CFL use less energy with comparable brightness and color rendition.
- *ECM 8 Landscape Shading of Building Façade:* The east and west facades of buildings in tropical zones experience the greatest exposure to solar energy that is absorbed into the façade walls. This action contributes much heat during the day to interior rooms that are adjacent to these walls. The broad leaf deciduous trees of the tropics that remain green year round can provide cooling shade from the rays of the high angled sun. Trees are especially effective on the façade receiving the most solar exposure. Hence this measure is used to add trees (7.62 m (25 ft.) tall) to the building east and west facades.

4.0 SIMULATION RESULTS AND ANALYSIS

4.1. Base-case energy use and thermal comfort

Figure 3 presents the annual total site energy consumption for the base-case models. The annual site energy use of base-case models are: 7,561 kWh/year with on-grade construction and 7,312 kWh/year with elevated slab. By end-use category, the base-case consumption includes: 28.2% to 30.6% for cooling and fans, 26.0% to 26.9% for lighting, 24.6% to 25.4% for equipment, and 18.8% to 19.5% for water heater.

The modeled energy consumption of base-case buildings were also compared against a previous study performed for similar residences in a neighboring region (Holmes and Kao (2010)). Holmes and Kao (2010) developed and analyzed an energy performance of an 83.6 m^2 (900 ft^2), single-family residential building using simulation for the U.S. Virgin Islands. The annual energy use index (EUI) reported in this analysis was 48.2 kWh/m^2-yr for a NV building with no AC systems; and 85.9 kWh/m^2-yr for an AC building. Meanwhile, the base-case models of this study with mixed-mode buildings involving both NV and conventional AC systems reported: 61.0 kWh/m^2-yr for on-grade construction; and 59.0 kWh/m^2-yr for elevated slab construction, which are between the two numbers reported in the U.S. Virgin Islands study.

Figure 4 presents the simulated indoor thermal conditions of the base-case models on the ASHRAE Standard 55 NV chart and psychrometric chart when the zones are occupied. The simulated hourly indoor temperatures varied between 21.4°C (70.6°F) and 27.2°C (81.0°F) for the Living Room zone; and between

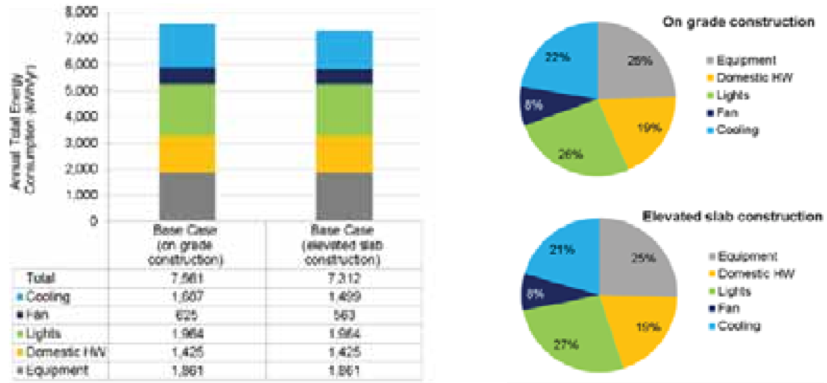


Figure 3: Annual total site energy consumption of base-case single-family residential models in the West Indies.

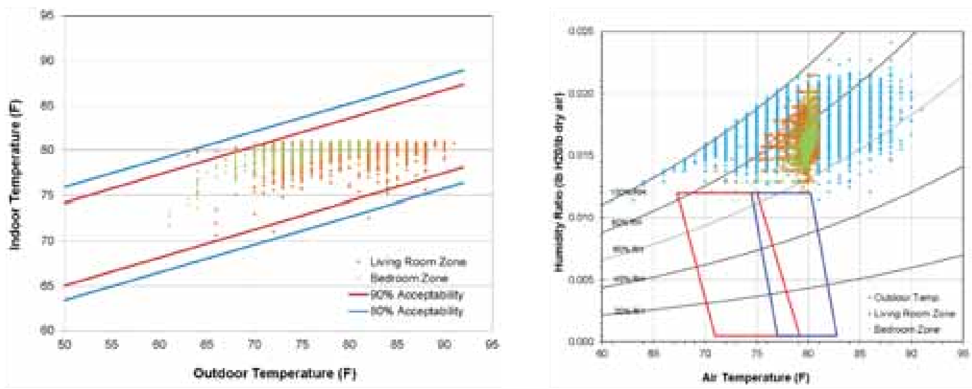


Figure 4: Simulated indoor thermal conditions of a base-case model (on grade construction) during occupied hours plotted on the ASHRAE 55-NV chart (Left) and the psychrometric chart (Right).

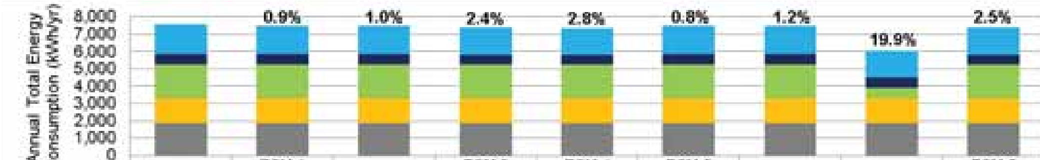
22.0°C (71.7°F) and 27.2°C (81.0°F) for the Bedroom zone, which fell within the ASHRAE Standard 55 NV's 90% thermal acceptability limits with negligible number of occupied hours within the 80% acceptability limits. However, when plotting the data on the psychrometric chart, it was found that the simulated indoor humidity levels were very high of which relative humidity ranged from 60% to 95% approximately.

4.2 Energy use reduction from various ECMs

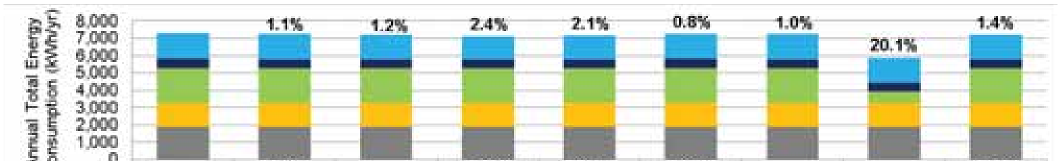
Figure 5 shows the annual site energy savings (%) above the base case achieved by each ECM. Compact Fluorescent Lighting options yielded the largest annual total energy reduction by reducing lighting, cooling, and fan energy uses: 19.9% to 20.1%. The measure yielding the second largest energy savings is energy efficient windows (2.1% to 2.8%). The landscape shading of the building (i.e., deliberated placement of vegetation around the base-case models) was also found to be effective in preventing radiant heat build-up within the dwelling (1.4% to 2.5%). Increased wall insulation measures also yielded a relatively good amount of savings: 2.4%. The savings from other measures were small, less than 2%.

4.3 Combined ECMs

All eight Energy Conservation Measures (ECMs) were combined and re-simulated as a group. Because the measures are interdependent in many cases, the resultant savings of grouped measures are not always the same as the sum of the savings of the individual measures. In a similar fashion as the analysis of the individual measures, the group measures were simulated by modifying all the parameters of combined individual measures. Figure 6 presents the annual total site energy savings (%) above the base case achieved by combined ECMs: 29.4% with on-grade construction and 28.1% with elevated slab construction. Although this study combined all ECM measures as an example, it is recommended a future study to be performed to select the best combination measures which should be based on payback period analyses.

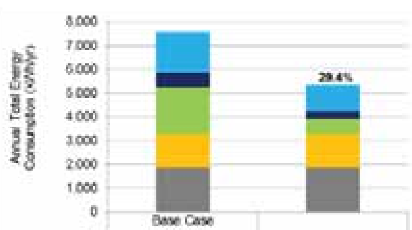


	Base Case	ECM 1 (Increased Roof Insulation)	ECM 2 (Radiant Barrier)	ECM 3 (Increased wall insulation)	ECM 4 (Energy efficient windows)	ECM 5 (Frame w/thermal break)	ECM 6 (Window overhang)	ECM 7 (CFLs)	ECM 8 (Landscape shading of Building)
Total	7,561	7490	7488	7383	7347	7497	7471	6055	7375
Cooling	1,687	1639	1638	1566	1540	1645	1625	1559	1558
Fan	625	602	601	568	558	603	597	573	568
Lights	1,964	1964	1964	1964	1964	1964	1964	638	1964
Domestic HW	1,425	1425	1425	1425	1425	1425	1425	1425	1425
Equipment	1,861	1861	1861	1861	1861	1861	1861	1861	1861

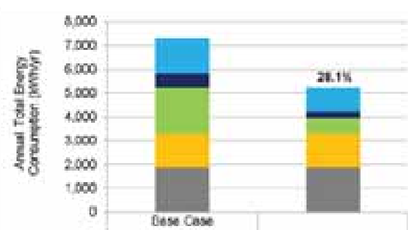


	Base Case	ECM 1 (Increased Roof Insulation)	ECM 2 (Radiant Barrier)	ECM 3 (Increased wall insulation)	ECM 4 (Energy efficient windows)	ECM 5 (Frame w/thermal break)	ECM 6 (Window overhang)	ECM 7 (CFLs)	ECM 8 (Landscape shading of Building)
Total	7,312	7234	7227	7133	7157	7253	7241	5840	7207
Cooling	1,499	1446	1441	1377	1394	1460	1451	1396	1426
Fan	563	540	537	507	514	544	541	520	532
Lights	1,964	1964	1964	1964	1964	1964	1964	638	1964
Domestic HW	1,425	1425	1425	1425	1425	1425	1425	1425	1425
Equipment	1,861	1861	1861	1861	1861	1861	1861	1861	1861

Figure 5: Annual total site energy consumption of individual ECMs: on-grade construction (Upper) and elevated slab construction (Below).



	Base Case (on grade construction)	Combined ECMs
Total	7,561	5,336
Cooling	1,687	1,123
Fan	625	289
Lighting	1,964	638
Domestic HW	1,425	1,425
Equipment	1,861	1,861



	Base Case (elevated slab construction)	Combined ECMs
Total	7,312	5,266
Cooling	1,499	1,051
Fan	563	282
Lighting	1,964	638
Domestic HW	1,425	1,425
Equipment	1,861	1,861

Figure 6: Annual total site energy consumption of combined ECMs: On-grade construction (Left) and (b) Elevated slab construction (Right).

5.0 CONCLUSION

This study developed base-case single-family residential models for the tropical humid islands of the West Indies and analyzed eight low energy conservation measures using the developed base-case models to determine potential energy savings from each individual measure as well as the combined group measures. The effects of the low energy measures on indoor thermal comfort were also studied. It was found that the simulated indoor thermal conditions generally fell within the ASHRAE Standard 55 NV's 90% thermal acceptability limits, but the simulated indoor humidity levels were very high of which relative humidity ranged from 60% to 95% approximately.

Although this study combined all ECM measures as an example, it is recommended a future study to be performed to select the best combination measures which should be based on payback period analyses. It is also recommended a study to be performed to analyze additional savings potential in other areas, including architectural design based on passive strategies, domestic hot water and equipment as well as renewables.

5.1. Recommendations for low energy residential buildings in the West Indies

Based on the results of the analysis, the following recommendations were developed for architects, engineers and homeowners in this region who wish to construct low energy residential buildings so as to avoid the needs for detailed analyses on every occasion when planning single-family residential buildings.

- Dwellings should be elongated on an east-west axis.
- Use double low-e glazing windows for all facades. Employing window shading when no other shading devices are employed. After these improvement are made to the windows, the window-to-wall ratio could be increased.
- Add insulation at the building enclosure, both at the roof/ceiling and exterior walls, to prevent solar heat gain on indoor occupied zones.
- Use compact fluorescent lights instead of incandescent lamps. This measure requires no additional construction activity, yet offered the greatest energy consumption reduction. This measure can be easily incorporated in existing dwellings.
- Consider planting trees around the site that would provide shade to the entire building. Broad leaf deciduous trees will provide shade throughout the year in tropical regions.

The proposed recommendations are expected to be widely used through consumer education programs that may also encourage the use of existing international *Building Energy Standards* and *Building Codes* in the residential building sector.

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