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Optimising Thermal Comfort through Passive Building Design in the Maldives

Aminath RASHEED

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Author's declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Aminath RASHEED

CENTRAL EUROPEAN UNIVERSITY

ABSTRACT OF THESIS submitted by:
Aminath RASHEED
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Six urban and rural buildings (a residential building and two commercial buildings each) were studied in the Maldives. The design features that could affect thermal comfort, the existing thermal environment in the building, and occupant characteristics that affect thermal comfort were observed. Comparison of the thermal preference of the occupants, indicated by the neutral temperature determined from a subjective thermal sensation vote, with the operative temperature of the buildings suggest that the thermal environment of all buildings, except the urban office building, do not provide adequate thermal comfort to its occupants. Comparison of the neutral temperatures indicated by thermal sensation vote and calculated predicted mean vote indicate that occupants engage in adaptive behaviours that enable them to tolerate thermally inadequate conditions. However, the high rate of adoption of air conditioners indicate that occupants increasingly resort to active (energy-intensive) measures to achieve thermal comfort, although the study of building design features suggest that there is huge potential for improving thermal comfort passively through improved building design. Several factors that limit the adoption of energy efficient building design were identified and analysed. The identified barriers could broadly be classified into three categories: lack of awareness, lack of incentive, and lack of resources. Since sustaining the effects of policies designed to increase adoption of energy efficient building technologies requires a fundamental change in the existing market for energy efficient buildings, a market transformation strategy, which includes a mix of legislative, economic and support policy instruments is recommended to address identified barriers.

Keywords: thermal comfort, building design, energy intensity, barriers, market transformation strategy

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1 Introduction

1.1 Background

Buildings account for around 30% of the total final energy consumption in the Maldives; a greater percentage than the amount of energy consumed by the country’s two main economic sectors (fisheries and tourism) combined (Riyan Pte Ltd. 2010). This is comparable to the global situation, as over 30% of global energy use and at least a quarter of global CO_2 emissions are attributable to buildings (Levine *et a*l. 2007). On the other hand, about 29% of the global emissions from residential and commercial buildings can be avoided cost effectively with currently available technology (Urge-Vorsatz *et al*. 2009). The reduction potential from the building sector represents the largest potential to reduce global CO_2 emissions among all the sectors considered in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Levine *et al*. 2007). However, this huge potential currently remains unrealized (Urge-Vorsatz *et al.* 2009).

The potential to reduce energy use and related emissions from residential and commercial buildings is highly significant to the Maldives, more so due to the country’s commitment to achieve carbon neutrality by the year 2020 (Ministry of Housing and Environment 2010). This will require significant efforts to reduce emissions from all sectors, and improving energy efficiency in residential, commercial and public buildings is one of the priority areas that are identified to be addressed in order to achieve carbon neutrality (Bernard *et al*. 2010).

While the potential for achieving Passive Housing or Net Zero Energy Building status has been studied and relatively well documented in more developed countries, mostly in cooler climates, this has been given less consideration in developing countries. However, it has been demonstrated that developing countries in warmer climates (such as the Maldives) could benefit from even larger and cheaper options to reduce energy use in buildings, especially in the form of electricity, as they have less need for space and water heating (Levine *et al.*

2007). As electricity is the final energy source used to provide for over 50% of the final energy demand in buildings in the Maldives (Riyan Pte Ltd 2010), potential reductions in electricity use represents a significant potential for reducing energy use and related emissions cost effectively.

The major focus of the Maldives' efforts to achieve carbon neutrality has so far been on generating energy from renewable sources. Several pilot projects for installation of roof-top photovoltaic solar panels has been carried out in the capital city Male', and some of the rural atolls (Nashid 2011). However, there have been practical and technological limitations to replacing fossil fuels with solar energy, at least in the short term, such as space limitations and the cost of storage technology. Hence, improving energy efficiency is extremely important to reduce energy use and related emissions. In addition to being cost-effective, improved energy efficiency will also reduce the scale of renewable energy projects required to meet the remaining energy demand (Bernard *et al.* 2010).

The major end-uses or energy services provided in buildings include provision of thermal comfort, refrigeration, illumination, communication and entertainment, sanitation and hygiene, nutrition, and other amenities. The total amount of energy used in buildings, as well as the relative energy consumption for the different end uses differ significantly. The building type/function and climate in which it is located are the most important factors that determine energy use patterns (United Nations Environtment Programme 2007). Residential buildings generally consume a greater proportion of the total energy consumption compared to commercial and public buildings. As energy demand for cooling is high in warmer climates, the greatest potential for energy savings in such climates is from space cooling (United Nations Environtment Programme 2007). As a hot humid country situated in the tropics, the energy demand for cooling in the Maldives is also expected to be highly significant. Hence, this study focuses on energy use for cooling.

The energy intensity (kWh/m^2) of a building reflects the climate, building type and building design. Hence, the energy performance of such buildings should theoretically be achievable for any building of the same type, under the same climatic conditions, by manipulating building design (Urge-Vorsatz *et al*. 2007). The energy intensity of the Maldivian building stock is expected to be higher than that of the Advanced Buildings, which adopt best practice in building design, with regard to thermal performance. Opportunities to improve building design in the Maldivian building stock to improve their energy performance can therefore be identified, by identifying the design features that affect energy performance, and comparing the characteristics of the existing building stock to the best practice.

Although building type and climate are the major determinants of energy use in a building, context-specific factors also have a significant impact on the amount of energy used in a building (Koppel and Urge-Vorsatz 2007), by affecting the rate and success of adoption of new energy efficient technology. Although adopting energy efficient technology at a large scale can lead to significant energy savings, and such technology is currently available at cost-effective prices, diffusion of energy efficient technology remain low (Jaffe and Stavins 1994).

The Carbon Trust identifies four major categories of barriers to improving energy efficiency in buildings- financial/ economic barriers, hidden costs/ benefits, market failures and behavioral/ organizational barriers (Carbon Trust, 2005). Koppel and Urge-Vorsatz (2007) include the two additional categories of information barriers and political/ structural barriers in their classification, although they may be classified as market failures.

The financial/ economic barriers refer to the additional investment required for the adoption of energy saving technology, while hidden costs/benefits are those not captured in financial terms. Real market failures refer to the characteristics of the market that prevent the investors from benefiting from investment in energy saving technology. The category of behavioural/

organisational non-optimalities refers to the behavioural features of individuals and organisations that prevent them from capturing the maximum benefits of the energy saving technology (Carbon Trust 2005). Lack of information on energy saving potentials is the other major category of barriers. The structural characteristics of the political, economic and energy system that obstruct investment in energy efficiency are also major barriers to energy efficiency in buildings (Koppel and Urge-Vorsatz 2007). All of these categories of barriers limit the adoption of the best practice in terms of building design, and limit the amount of energy savings provided by improved building design. While some of these barriers have been studied fairly well, other barriers, especially pertaining to culture and behavior, as well as institutional features have not been studied in depth. Furthermore, existing studied tend to focus on developed countries, rather than developing countries (Urge-Vorsatz *et al*. 2009)

1.2 Research Question

Given the importance and potential to reduce energy consumption in buildings of the Maldives, in order to achieve its goal of carbon neutrality by 2020, the major aim of this study is as follows.

To determine the barriers to reducing energy demand for thermal comfort in Maldivian buildings through improved building design, and suggest a strategy for overcoming the barriers.

To this end, the objectives of the study are as follows:

1. To determine the existing characteristics of the Maldivian building stock with regard to their design features and thermal performance, and the behavioral characteristics of Maldivian building occupants that determine their energy requirement for thermal comfort.
2. To determine significance of the barriers to energy efficiency in the Maldives, with regard to financial/economic barriers, hidden costs, market failures, behavioral factors, informational barriers and structural barriers
3. To propose a strategy to address the identified barriers, in order to increase the adoption of energy efficient building designs and components

1.3 Scope

The building types studied are limited to residential buildings, offices and restaurants. The barriers identified and the strategy suggested to overcome the identified barriers pertain only to barriers to adopted energy efficient building design, and does not explicitly address energy efficient equipment, urban design, or occupant behavior (although some of the barriers and suggested remedial measures may address the latter factors as well). The building design characteristics and occupant characteristics have been studied only with regard to energy demand for thermal comfort; other energy services demanded in buildings are not explicitly addressed.

2 Theoretical Framework

2.1 Thermal Comfort

The energy demand for providing the energy service of thermal comfort in the hot humid climate of the Maldives refers to energy spent on space cooling, rather than space heating. Thermal comfort refers to a "condition of mind that expresses satisfaction with the thermal environment" (ASHRAE 2003, 7). This perceived state is determined by physiological as well as psychological factors (Baker 1987; ASHRAE 2003).

From a physiological standpoint, thermal discomfort (i.e. perception of being "too cold" or "too hot") is felt when there is an imbalance between metabolic heat gain and heat loss from the body, the continuation of which would result in damage to the body (Baker 1987). Although metabolic heat generation enables humans (and other warm-blooded animals) to inhabit environments that are cooler than their body temperature, metabolism usually creates excess heat that needs to be lost to the environment (Baker 1987). This is achieved by three main mechanisms: radiation, convection, and evaporation (conductive heat loss is less significant in this respect).

Table 1 Features of the three main heat loss mechanisms

	Mechanism of Heat Loss	Requirements for Heat Loss	Environmental Parameters that Control Heat Exchange
Radiation	Transfer of heat from the body surface to surrounding surfaces	Body surface at higher temperature than surrounding surfaces	Mean Radiant Temperature (area-weighted mean of the temperature of the surrounding surfaces)
Convection	Transfer of heat to the air in contact with the body surface	Body surface at higher temperature than air in contact As air is a bad conductor, this requires the warmed air to be removed by an air current	Air temperature Air movement
Evaporation	Heat from the body surface is used to evaporate perspiration	Relative humidity less than 100% Removal of warm air layer in contact with the body	Relative humidity Air movement

Environmental parameters that determine thermal comfort (i.e. temperature, humidity/ amount of moisture in the air, air movement) in a building can be affected by non-climatic factors, in addition to climatic factors such as solar radiation (sky conditions), wind speed and direction and relative humidity. Major casual sources of heat include occupants, lighting and equipment. The heat output from these sources is of two types: latent and sensible. Latent heat generation increases relative humidity, while sensible heat generation increases air temperature (Baker 1987). The environmental parameters of thermal comfort combine to provide the thermal conditions in a particular environment.

2.1.1 Thermal Comfort Standards

The American Society of Heating, Refrigeration and Air-Conditioning Engineers Inc. has developed a standard for Thermal Environmental Conditions for Human Occupancy (Standard 55P), which "specifies conditions in which a specified fraction of the occupants will find the environment thermally acceptable" (ASHRAE 2003). In this case, the standard aims to determine conditions acceptable to 80% of the occupants.

This standard is based on six primary factors that define the conditions for thermal comfort. These are the four environmental parameters of air temperature, mean radiant temperature, air velocity and air humidity, in addition to physical activity and clothing (ASHRAE 2003). These factors are used to calculate the Predicted Mean Vote (PMV), which predicts the mean vote of a large group of people on a 7-point thermal sensation scale (Figure 1).

+3	Hot
+2	Warm
+1	Slightly Warm
0	Neutral
-1	Slightly Cool
-2	Cool
-3	Cold

Figure 1 ASHRAE 7-point thermal sensation scale (Source: ASHRAE, 2003)

The calculated PMV can be used to check whether the thermal conditions in a building fits the comfort criteria, or to establish thermal requirements or predict combinations of factors that will provide neutral conditions (PMV=0). The Predicted Percentage of Dissatisfied people (PPD) can also be determined from the PMV, assuming that votes of +3, +2, -3 and -2 correspond to dissatisfied people, and PPD is symmetric with neutral PMV as the centre (ASHRAE, 2003).

A Thermal Comfort Zone (i.e. range of temperatures that provide acceptable thermal conditions) can be determined for a given combination of humidity, air speed, metabolic rate and clothing insulation. The Thermal Comfort Zone is defined in terms of the operative temperature (T_{op}), which is the average of air temperature and mean radiant temperature weighed by the coefficients of convective heat transfer and linearised radiant heat transfer. The ambient operative temperature (T_{op}) indicates the prevailing thermal conditions within the building (ASHRAE 2003).

While the PMV calculation provides a reliable method for predicting the thermal performance of a building, it is subject to adaptive errors, which arise due to behavioural adjustments by occupants to mitigate thermal discomfort. The adaptive strategies adopted by occupants are highly context-specific and not usually accounted for in conventional models such as the PMV index (Rajasekar and Ramachandraiah 2010). A subjective survey to determine the actual thermal sensation vote (TSV), i.e. the actual mean vote of occupants on the 7-point thermal sensation scale (Figure 1) usually yields quite different results from the calculated PMV ((Rajasekar and Ramachandraiah 2010; Feriadi and Wong 2004). The neutral temperature (T_n), i.e. the temperature at which most people vote within the "neutral" (PMV=0) category can be determined as an indicator of the thermal requirement of the occupants.

2.1.2 Thermal Comfort in Buildings in Warm Humid Tropical Islands

Warm humid tropical climates are situated between 15° North and South of the equator. It is characterised by high air temperatures, high precipitation and high relative humidity of about 75% throughout the year. Daytime temperatures range between 27°-32°C, while the nighttime temperatures range from 21°-27°C. Winds are generally low and the direction changes with the monsoons (Baker 1987). In islands in this climatic region, humidity can range from 55% to 100%, while the high air temperatures, small diurnal temperature range, high precipitation and relatively low winds characteristic of the warm humid climate zone persist (Baker 1987).

The most dominant factor affecting thermal comfort in tropical buildings is exposure to solar radiation. As the outside air temperature is usually above the comfort zone, any exposure to solar radiation results in thermal discomfort to occupants. Retention of heat within the structure leads to nighttime discomfort (Baker 1987). Provision of thermal comfort in this climate therefore requires space cooling.

2.2 Regulating the Thermal Environment in Buildings

The thermal environment of a building can be manipulated by either active or passive measures. Active measures require energy and involve the use of cooling and/or ventilation equipment such as electric fans and air conditioners. Passive measures do not require energy and include design features that enhance cooling and ventilation or reduce heat gain (Baker 1987).

The environmental parameters that control the mechanisms of heat exchange can be manipulated to alter heat gain into and heat loss from the building, using passive design features. The strategies for improving the indoor thermal conditions in a warm humid climate include reducing the temperature, thereby reducing radiative and convective heat gain from the environment, and increasing air movement to facilitate evaporative heat loss to the environment. Although temperature and air movement can be controlled quite easily by manipulating building design, relative humidity is more difficult to manage passively (Baker 1987).

Reducing the indoor temperature significantly below the outdoor temperature is very difficult in this climate due to the small diurnal temperature range. Hence, the main design objective is to avoid exceeding the outdoor temperature by screening the building from exposure to solar radiation, avoiding retention of heat within the structure, and maximising the use of air movement to encourage evaporative cooling (Gut and Ackerknecht 1993). The reliable breeze experienced in the tropical island climate is therefore instrumental in enhancing thermal comfort (Baker 1987).

Design variables that affect the thermal environment of the building include building layout and siting, thermal properties of construction materials, location and size of openings, shading of the envelope and openings, surface treatment of the envelope and insulation (Bouchlaghem 2000).

2.2.1 Reducing Heat Gain from the Environment

Solar radiation is the major source of heat in buildings. Solar heat can be transmitted into the building through the building fabric and through openings in the building envelope (Baker 1987). Reducing the solar heat gain primarily involves minimising the exposure of the building to incident solar radiation and reducing the amount of radiation absorbed by the building fabric and through openings in the building envelope.

Incident radiation can be minimised through orientation and layout considerations, and use of external shading devices. The solar radiation reaching the building can be reflected, transmitted, or absorbed (Baker 1987). Opaque materials either reflect or absorb light, while transparent materials also allow light to be transmitted through it (ACI Committee 122 2002).

Exposure to Incident Solar Radiation

The amount of solar radiation reaching the building can be minimised by careful consideration of its orientation, and by using devices to shade both the openings and walls that are exposed to solar radiation (Baker 1987). The warm humid climate of the tropics result in high levels of moisture in the atmosphere, which means that buildings receive significant amounts of diffuse radiation reflected from the water droplets in the air, in addition to the direct radiation from the sun (Gut and Ackerknecht 1993; Baker 1987).

Orientation- the optimum orientation for minimising solar heat gain through the building fabric and openings is along the east-west axis. This is because a roof overhang can then provide sufficient shading to the longer north and south facades (Wong and Li 2007). However, the east and west facades will be exposed to solar radiation from much lower angles in the morning and evening (Baker 1987; Gut and Ackerknecht 1993). While some shading from adjacent buildings and vegetation is usually available, shading devices often need to be used to minimise ingress of direct and diffuse radiation into the building (Baker 1987).

There is often a conflict between orientation needs for maximising access to prevailing winds and minimising exposure to solar radiation. In the Maldives, the direction of the prevailing winds change with the monsoons. The strength and direction also depends on the proximity to the equator, which is straddled by the country. The Northeast monsoon lasts from January to May, and results in moderate winds in the northern part of the country. The south receives winds from the north-west during this monsoon. Strong winds are experiences in the country's north in the South-West monsoon, lasting from May to November. The western monsoon winds remain strong in the south of the country as well (National Renewable Energy Laboratory 2002). Due to the variable nature of the wind resource throughout the year, orientating the buildings to minimise solar ingress, combined with adjustable projections to deflect the prevailing winds into the building might prove to be the optimum solution.

External Shading Devices- Overhanging roofs, projection slabs, grills, etc. are used to protect the interior from solar radiation (Gut and Ackerknecht 1993; Baker 1987; Wong and Li 2007). The large size of the openings, required to admit prevailing breezes into the building, and due to the need to obstruct a large portion of the sky (and not only the sun, due to the high contribution of diffuse radiation) necessitates large shading devices (Gut and Ackerknecht 1993).

The north and south facades can be shaded efficiently, especially from the midday sun, using horizontal elements, such as roof overhangs, projection slabs and louvers. The east and west facades are best protected from the morning and evening sun using movable vertical screenings, such as window shutters and doors. A combination of horizontal and vertical devices, called the 'brise soleil' is sometimes used when horizontal or vertical shading alone is insufficient, for instance on the southeast and northwest facades (Gut and Ackerknecht 1993; Baker 1987). In Male', lying about 4 degrees north of the equator, horizontal shading elements on the southern facade needs to be longer than on the northern facade, since the deviation of the sun's path to the south is greater than that to the north. A small overhang on the northern facade is nonetheless required to provide shading when the sun's path is north of the equator, due to the tilt of the Earth's rotational axis.

Layout- Layout of the rooms must ideally be decided with consideration of their occupancy schedules and functions. For instance, bedrooms are mostly occupied in the evenings, and hence could be placed in the eastern side, where it is cool in the evening. As the human body is particularly sensitive to its thermal environment when at rest, proper thermal conditions are especially important in the bedroom, where activity level is typically low (Baker 1987). On the other hand, rooms which are used during most hours of the day for relatively more intense activities (such as the living room) should ideally be placed in the north and south sides, which are protected from direct sunlight. Detaching rooms with internal heat loads (such as the kitchen) from the main building can also reduce internal heat gains. Although detached kitchens are a common feature in rural residential buildings of the Maldives, this is no longer feasible in most places as land is rapidly becoming scarce, especially in Male'.

Gains through Building Envelope

Components of the building envelope include walls, roof, windows and the floor. If exposure of these components to solar radiation is not avoided through layout and orientation or external shading devices, incident radiation has the potential to reach the building interior through these materials. Incident radiation is either reflected or absorbed by opaque surfaces, while transparent materials can also allow radiation to be transmitted through them as well (ACI Committee 122 2002).

Reflectivity - The only fraction of incident radiation that is eliminated from the building interior is that which is reflected from the surface. Hence, reflective finishes on external surfaces reduce the heat gain (Baker 1987; Wong and Li 2007). Increasing the reflectivity of the inner surface of ceilings in double roof ventilation arrangements can reduce heat gains from radiative heat flow to the ceiling from the roof, as the radiation is reflected back up. This can be achieved by adding a sheet of aluminium foil or other shiny metal to the inner ceiling surface (Baker 1987).

Thermal mass- The fraction of radiation that is not reflected contributes to the thermal mass of the building envelope. Thermal mass or thermal inertia refers to the absorption and storage of heat in the building envelope (ACI Committee 122 2002). Although thermal mass can be used to effectively delay and reduce the peak in temperature within the building, the low diurnal temperature range in tropical climates limits the effectiveness of this effect in such climates. This release of daytime heat gain in the evening leads to discomfort, which is compounded by the fact that the relative air movement is lower at night when activity level of occupants is lower (Baker 1987). However, some amount of thermal storage (along with night-time ventilation) may be advantageous in buildings/ rooms that are occupied only during the day, in order to introduce a short lag time such that the heat from the day reaches the interior during the unoccupied hours and is removed by effective ventilation during the night (Gut and Ackerknecht 1993).

The effect of thermal mass depends on the thermal properties of the construction material (conductivity, absorptivity, emissivity, specific heat capacity and thermal diffusivity) as well as the location and thickness of the mass, insulation and the daily temperature range (ACI Committee 122 2002).

Absorptivity and Emissivity–Absorptivity is defined by the fraction of incident light that is absorbed by the material, and not reflected or transmitted. Emissivity is the effectiveness with which stored heat is released from the mass. Light coloured materials are recommended for the building fabric, as they have low absorptivity and emissivity of solar radiation, whereas dark coloured materials have high absorptivity, leading to transfer of heat to the interior (Baker 1987; ACI Committee 122 2002). Recommendations for light colours apply to interior surfaces, curtains, blinds, etc. High absorptivity materials like heat-absorbing glass is generally of low effectiveness as some of the absorbed heat reaches the interior through convection or as emitted long wave radiation (Baker 1987). Similarly, tinted glass also absorbs some of the heat and light energy from solar radiation, but the some of the absorbed heat is transferred to the interior via convection and radiation, and the overall reduction in heat gain is less the accompanying loss in light transmittance (Baker 1987). The effectiveness of self-reflecting glass is also limited, as they reduce the light gain by as much as they reduce the heat gain, increasing the need for artificial lighting and thereby increasing the heat gain from artificial lighting.

Conductivity and Insulation- insulation reduces the conductivity of the building fabric. Conductivity is the rate at which heat passes through the material. While conductivity is the property that allows heat to be transmitted through the material for storage, materials with high conductivity also have low capacity for storage as the time lag or delay in heat transfer is small.

The location of insulation relative to the thermal mass is very important (ACI Committee 122 2002). Coupling the mass with the interior and insulating the building from the outside is useful in warm humid climates, as this allows heat gain from the interior but not so much from the external environment (Baker 1987). This is because of the limited capacity for transferring heat to the outside, as the outside climate is usually overheated.

Insulation may be of limited use in naturally ventilated buildings in the warm humid climate, since exchange of air between the interior and the external environment is required, which will maintain similar temperatures inside and outside the building. Furthermore, insulation will also reduce the potential for heat loss from the building if the outside temperature falls below the thermal comfort requirement (Gut and Ackerknecht 1993). Considering the limited effectiveness of insulation due to the small difference between internal and external air temperatures, it may be beneficial only in sun-exposed surfaces (Baker 1987). In the dense built environment of Male', most walls are not exposed to the sun significantly. Hence, roof insulation may be the most useful in this respect.

Roof insulation in the form of a ventilated double roof can be very effective in reducing heat gain through the roof (Wong and Li 2007; Gut and Ackerknecht 1993). This can be achieved by installing a ceiling beneath the roof, with a small void between the two layers (Baker 1987). Heat is transferred between the roof and the ceiling mainly by radiation and to some extent by conduction. No convection currents occur, as the roof is at a higher temperature than the ceiling below (Gut and Ackerknecht 1993). If air is enclosed between the two layers, the temperature in the void can rapidly increase and lead to conductive heating of the ceiling. However, leaving the void open to the outside will allow heated air to be removed, thereby minimising the conductive heat transfer. This will can also reduce the temperature of the inner surface of the roof, and thereby reduce the radiative heat transfer from the roof to the ceiling (Gut and Ackerknecht 1993; Baker 1987).

2.2.2 Increasing Heat Loss to the Environment

Heat exchange via convection is enhanced by air movement. Hence, higher air velocity can compensate for increased temperatures, and influence the thermal sensation of occupants (ASHRAE 2003). Increasing airflow is therefore a common strategy used in warm humid climates to improve thermal conditions. Although this usually involves the use of an electric fan in modern urban buildings, design features can also greatly enhance airflow into the building, and improve the thermal conditions passively.

Related to air movement is ventilation, or replacement of internal air with cooler external air. Whereas air movement increases heat loss from the body to the environment via convection, ventilation reduces the indoor temperature by replacing internal air with cool external air. Despite this distinction, ventilation cannot be achieved without air movement. On the other hand, air movement without ventilation is possible, but only with the use of an electric fan (Baker 1987).

In warm humid climates, the most effective use of air movement to improve thermal comfort inside a building is to increase airflow at body level, rather than provide structural cooling as in hot dry climates (Baker 1987; Gut and Ackerknecht 1993). Air movement requires a pressure gradient, as air flows from high pressure to low pressure areas. Although the pressure gradient can arise from wind action, or differences in temperature, the effect of wind tends to dominate in warm humid island climates, with highly consistent breezes (Baker 1987).

Although evaporative cooling is highly effective in reducing temperatures, it is not suitable for tropical island climates with their high ambient humidity. This is because the increase in humidity from the evaporative coolers would reduce the latent heat loss by reducing the rate of evaporation of sweat. The resulting sensation of increased sweating would cause discomfort, which would counteract the effect of the decrease in temperature (Baker 1987).

Access to Prevailing Winds

Maximising benefits from wind driven air movement requires several design considerations, beginning with the siting and location of the building. Staggering the layout of buildings within the settlement prevent rows of buildings located downwind from being shaded from the incident winds by buildings on the windward side. Locating high-rise buildings on the leeward side of low-rise buildings can also improve access to the prevailing winds. In Male', the direction of prevailing winds varies from northeast to south-west in the two monsoons. Due to the variable nature of the wind resource, locating low-rise buildings in the periphery of the city, and high-rise buildings in the interior would provide optimum access to the wind to all buildings. However, the existing buildings in Male' have not been built with such considerations, and the access to prevailing winds depend on the height of the building in relation to the surrounding buildings, and the spacing between buildings.

Buildings should not be grouped together in too compact a manner, as this would create resistance to the prevailing winds. However, adequate spacing between buildings is difficult to achieve in dense settlements such as Male', where adjacent buildings are typically built with minimal spaces between them. Hence, the location of the building in relation to the coast could also be important in an island such as Male', as the resistance to prevailing winds near the coast is lower than that in the interior.

Concerns for privacy, security and access to insects also restrict access to prevailing winds in dense settlements (Mallick 1996). While louvered or overlapping screen walls and fences, and placements of grills and netting around balconies (rather than on windows), may provide a solution since they can be used to obstruct direct view, yet allow some amount of air to penetrate in, the air velocity is also significantly reduced by such devices.

The optimum orientation for access to prevailing winds might conflict with the optimum orientation for shading from solar radiation. As air movement can be manipulated by the layout of buildings, as well as devices to deflect incoming winds, a compromise is often possible (Baker 1987). Low-rise buildings are usually protected from direct solar radiation from nearby buildings and vegetation. High-rise buildings, on the other hand, have better access to prevailing winds but less protection against solar radiation from the surroundings. The high wind velocities experienced at higher building heights is very influential in reducing temperatures within the building. However, the highest temperatures are experienced in middle floors with lower wind velocities, but high exposure to solar radiation (Wong & Li 2007). Hence, orientation and height both affect the amount of wind and solar radiation to which the building is exposed (Baker 1987).

Deflection of Incoming Air

Openings- Large, fully operable openings are preferred in warm humid climates, to allow access to prevailing winds. The size and location of openings such as windows affect the velocity and route of airflow within the room.

Larger openings increase the air velocity inside the building, if both the inlet and outlet are enlarged. A larger outlet relative to the inlet will further increase the velocity, by creating a pressure gradient (Gut and Ackerknecht 1993). Asymmetric placement of the openings will also create unequal pressure on either side of it, thereby affecting airflow through the opening.

Fins, Projection Slabs and Louvers- Fins, projecting slabs and louvers can also be used to affect the pressure and therefore the velocity and direction of airflow through the openings (Gut and Ackerknecht 1993). A canopy or projection device above the opening results in an upward deflection of incoming air, suitable for cooling the ceiling/ roof. On the other hand, leaving a gap between the wall and the projection, using a longer projection at a slightly higher relative position, or installing louvers in the window creates a more direct flow of air, which is more likely to impinge on the occupant (Gut and Ackerknecht 1993; Baker 1987). Adjustable louvers are advantageous as they can be adjusted according to angle of incidence of prevailing wind, required air velocity and direction, and closed when needed (e.g. during storm conditions).

Ventilation

Cross Ventilation- Cross ventilation, with two openings on opposite sides of the room, provide better air movement and ventilation, as air penetrates deeper into the room than with single-sided ventilation (Baker 1987). As internal partitions can alter airflow and possibly reduce air velocity, they must be placed so that airflow is not impeded. It may be possible to ventilate a greater area of the room by creating a turbulent air circulation within the room through careful placement of obstructions (Gut and Ackerknecht 1993). Openings in internal partitions between rooms is important for effective cross ventilation in double (or more) banked rooms (Gut and Ackerknecht 1993). Cross ventilation is even more effective in single-banked rooms with access to building-adjacent open areas (like verandas and galleries). However, this is rarely possible in the dense urban environment on Male', and increasingly in the rural villages as well.

Displacement Ventilation- Temperature-driven air movement can be used to produce displacement ventilation via the 'stack effect'. This effect can be created by placing openings near the top and bottom of a wall, allowing warm air to move out through the top opening and cooler air to enter through the lower opening, as warm air is lighter than cool air and therefore rises (Gut and Ackerknecht 1993).

Air velocity due to stack effect depends on area of the openings, distance between them, and the difference between indoor and outdoor temperatures. As high internal temperatures are required to sustain the air movement, this may not be an ideal feature in occupied spaces. However, it might be possible to use an unoccupied area to create a draught within the occupied areas of the building. A solar chimney is a structure where the stack effect is applied in this manner to maximise solar heat gain and ventilation effect (Gut and Ackerknecht 1993; Baker 1987).

The different components of a building can be designed according to the abovementioned basic principles, in order to improve its thermal performance, by reducing heat gain and increasing heat loss.

2.3 Barriers to Reducing Energy Demand for Thermal Comfort

Improving building design to enhance thermal comfort reduces the energy demand for thermal comfort. However, both the extent to which energy efficient building design is adopted in the country and the effectiveness of the adopted energy efficient design can both be limited due to several different factors that are context-specific. These include economic, technical, cultural and institutional factors, all of which contribute to the ultimate reason that prevents adoption of energy efficient technology, which is the greater (real/perceived) cost of energy efficiency compared to the benefits it offers.

2.3.1 Economic Barriers

Energy efficient technology usually has a higher upfront cost, compared to conventional technology (Urge-Vorsatz *et al*. 2007; Levine *et al*. 2007). This cost usually does not reflect the externalities of electricity use, such as environmental degradation, making conventional technology appear more attractive, in purely monetary terms (Urge-Vorsatz *et al*. 2007;

Carbon Trust 2005). The operating cost of energy efficient technology is generally lower for the household or organization, largely owing to the energy savings. However, the limited availability of capital and limited access to capital markets, especially by low-income households and small businesses that are too small to attract investors and financial institutions, limits their ability to obtain energy efficient technology (Urge-Vorsatz *et al*. 2007; Levine *et al*. 2007).

On the other hand, high-income households and large organizations often lack the motivation to invest in energy efficiency, despite their financial ability to do so, as their expenditure on energy is a relatively small fraction of their expenses (Urge-Vorsatz *et al*. 2007). This, coupled with the large transaction costs associated with adopting energy efficient technology, (Urge-Vorsatz *et al*. 2007), reduces the attractiveness of energy efficiency ventures to parties that are in the best position to adopt energy efficiency measures (Carbon Trust 2005).

Many developing countries also have subsidies for energy. While these create a disincentive for energy efficiency, cessation of the subsidy suddenly can also lead to theft and non-payment, rather than encourage energy efficiency (Urge-Vorsatz *et al*. 2007; Levine *et al*. 2007).

2.3.2 Hidden Costs

Some of the costs associated with the use of energy efficient technology are not reflected in financial flows. These include costs and risks that are real as well as those that are perceived (Urge-Vorsatz *et al*. 2007). Reliability, ease of servicing and compatibility with existing accessories (such as fittings for equipment) all present potential costs, if conventional technology have better performance than energy efficient technology (Urge-Vorsatz *et al*. 2007). The quality and reliability of energy service itself is important, as subpar energy services can limit the effectiveness of energy efficient technology, or even cause damage to them (Urge-Vorsatz *et al.* 2007).

Transaction costs may also be a significant source of hidden costs. These include the cost of obtaining information, preparing projects, negotiating contracts and implementing energy efficiency projects (Carbon Trust 2005; Urge-Vorsatz *et al*. 2007). Such costs are likely to be higher before energy efficiency measures have become widespread, due to the lack of experience in energy performance contracting (Levine *et al*. 2007) and energy efficiency projects in general.

2.3.3 Market Failures

Market failures prevent the benefits of energy efficiency from reaching those who undertake energy efficiency measures (Carbon Trust 2005). In addition, while societal benefits from investment in energy efficiency may be large, there may not be enough incentive for an individual household or organization to adopt such technology that have large up-front costs and are not proven in the specific local context (Carbon Trust 2005). Potential adopters of the energy efficient technology may delay adoption with the expectation of lower prices in the future (Jaffe and Stavins 1994).

Fragmentation of the market structure is particularly pertinent to the building sector, and the typically linear and sequential process of designing and constructing a building, with division of responsibilities, does not encourage systemic thinking that is necessary to minimize energy use from the building's entire system. The lack of cooperation and coordination between architects, contractors and engineers lead to suboptimal results with regard to the level of energy efficiency achieved by the adoption of energy efficient technology (Urge-Vorsatz *et al*. 2007; Levine *et al*. 2007). On the other hand, the widespread adoption of energy efficient technology itself requires industry-wide acceptance and co-ordination (Dewick and Miozzo 2004). However, this is hard to achieve in the fragmented construction industry, especially given the aversion to new technology, the reception of which by clients and other industry players is uncertain (Unruh 2000).

It is often difficult to introduce new ideas and solutions outside the existing technological paradigm, as the cognitive framework (rules, heuristics, principles) that determine the technology used, depends on past knowledge, experience and achievements (Perkins 2003). Vested interests and biases may also restrict the cognitive horizons of the actors in the industry (Kemp 1994). The conventional approach to contracting in the industry is also characterized by mutual distrust, lack of communication and limited time and money, all of which present barriers to identifying and implementing new energy efficient technology (Dewick and Miozzo 2004).

Furthermore, the developer of a building is often different from the end-user, which creates different incentives for the two parties involved. While the developer is interested in minimizing the cost of construction, the end-use has more to gain from energy efficiency measures. This is also the case in rented residential buildings, where the interest of the landlord is to minimize upfront cost, while the lessee is interested in maximizing energy efficiency, but has limited control over the equipment and design of the property. Likewise, energy service providers have no direct incentive for reducing the energy used by consumers (Koppel and Urge-Vorsatz 2007). This phenomenon is often referred to as principal-agent barrier (Urge-Vorsatz *et al*. 2007).

2.3.4 Behavioral Characteristics

Differences between countries of similar climatic and economic characteristics in their energy use patterns illustrate the influence of lifestyle and tradition on energy use (Levine *et al*. 2007). Culture and behavior play a key role in determining the amount of energy used in buildings. The thermal requirement of the occupants is the major occupant characteristic that affect the amount of energy required to provide thermal comfort.

The thermal requirement is dependent on physiological and psychological characteristics of occupants. The physiological requirements for thermal comfort are more or less inflexible.

Behavioural adjustments can increase the level of thermal comfort provided by the thermal performance of the building (determined by building design and climate). On the other hand, psychological factors can alter the level of thermal comfort required by the occupants, and thereby affect behaviour. Behaviour is often engrained in culture and therefore difficult to alter in the short term. Hence, cultural factors that increase the level of thermal comfort either experienced or demanded by the occupants in the prevailing climate are important in determining the potential for addressing thermal discomfort through building design.

The physiological cooling requirement is affected primarily by the level of metabolic activity and clothing. While metabolic activity generates heat, clothing as acts an insulator (Baker 1987). Altering activity level/ schedule and type of clothing in response to the climate are therefore common adaptive strategies to address unmet thermal comfort requirements, and cultural practices of clothing and working are highly reflective of the prevailing climate. Hence, clothing and metabolic activity are included in the factors used to determine the PMV in the ASHRAE standard. Additional factors that are not considered in the ASHRAE can also influence the cooling demand.

Metabolic activity results in generation of heat. Therefore, increase in the level of metabolic activity leads to a decrease in the preferred temperature (Baker 1987). The ASHRAE Standard specifies the metabolic rate for different activities, to be used in the calculation of the PMV. The values are time-averaged, as instantaneous changes in metabolic rate do not alter thermal comfort significantly. The values also apply to individuals, rather than to a space, as different individuals engaged in different activities in the same space experience different thermal sensations (ASHRAE 2003).

Clothing provides insulation, and thereby retards heat transfer between the person and the environment. Therefore, heavy clothing leads to greater discomfort and the requirement for cooling increases. The insulation values, measured in clo, for different clothing ensembles and garments are also specified in the ASHRAE Standard, to be used in calculating the PMV.

In addition to changing clothes or changing the level of metabolic activity, passive adaptive behaviours such as opening windows/ doors, drinking cold drinks, taking a cool shower, using outdoor spaces, etc. can also lower the amount of energy required to meet the thermal requirements of the occupants (Feriadi and Wong 2004; Wong *et al*. 2002). In fact, it has been suggested that occupants preferably change behaviour rather than the environmental conditions, in response to thermal discomfort (de Dear and Leow 1990). Since such strategies are not considered in the PMV calculation, the PMV score is often underestimated. (de Dear and Leow 1990) Errors in conventional models that predict the PMV and related indices of thermal comfort, called 'adaptive error', arise due to such adaptive behaviours of building occupants (Rajasekar and Ramachandraiah 2010).

This is especially true for hot humid countries, where cultural practices are often shaped by the prevailing climatic conditions (Feriadi and Wong 2004). Several studies have found that inhabitants of tropical countries have a higher range of acceptable thermal conditions than those specified by the ASHARE standards (Feriadi and Wong 2004; Mallick 1996; Rajasekar and Ramachandraiah 2010; Wong et al. 2002; de Dear and Leow 1990). Furthermore, occupants of residential buildings have greater flexibility in the adaptive measures available to them, compared to occupants of non-residential buildings, such as offices (Feriadi and Wong 2004). However, microclimatic conditions, such as noise and air pollution in urban environments, present significant constraints to the adoption of adaptive strategies (Rajasekar and Ramachandraiah 2010). Hence, calibration of the model to the Maldivian context will require consideration of such cultural factors and differences between different building types and their microclimatic conditions as well.

The psychological factors that affect the cooling requirement of inhabitants include previous thermal experience, acclimatisation to the prevailing climate, and perhaps the level of awareness and attitude towards issues pertaining to the environment / sustainability.

Thermal experience has a significant influence on the thermal comfort requirements of occupants, as indicated by the observed difference in the preferred temperature of occupants working in air-conditioned and non-air conditioned spaces, and the correlation between mean outdoor temperature in the preceding week and the thermal preferences (Rajasekar and Ramachandraiah 2010).

2.3.5 Information Limitation

The availability, reliability and completeness of information on energy efficient technology are often insufficient (Urge-Vorsatz *et al*. 2007). Information regarding the method of use and profitability of new technology is often limited (Jaffe and Stavins 1994). Imperfect information further complicates the necessary trade-off between energy savings from energy efficient technology against the higher investment cost, since it requires comparing the discounted value of energy savings with the current price of the technology, which is difficult to understand and calculate (Levine *et al.* 2007). For instance, energy bills provided to end-users usually does not include a breakdown of individual end-uses and associated emissions, which limits their understanding of the potential energy savings that investment in efficiency can provide (Levine *et al.* 2007).

On the other hand, actors in the building industry and regulatory authorities usually have limited training in energy efficient technology and best practice, which are quite recent and rapidly improving (Levine *et al*. 2007). Energy efficient housing is not a common part of architecture courses even in developed countries (Urge-Vorsatz *et al*. 2007).

2.3.6 Structural Barriers

The institutions that influence the building industry, such as the government authorities that regulate the industry and financial institutions that provide capital, can also be the source of considerable barriers to penetration of energy efficient technology in buildings. Factors such as the level of interest of the authorities in energy efficiency, adequacy of enforcement structures and policies, availability of qualified personnel and the level of corruption in the public institutions can be important in determining whether or not energy efficient technology are adopted in the country easily (Koppel and Urge-Vorsatz 2007). Policies of other government institutions such as the environmental policies that restrict development, and policies regarding investment, taxation, procurement etc., also have an impact on the building industry and the ease with which new technology can be introduced (Levine *et al*. 2007; Kemp 1994).

Financial institutions traditionally have asset-based lending practices and are conservative and risk-averse, all of which can be barriers to financing new energy efficiency initiatives in buildings (Levine *et al*. 2007; Unruh 2000). While venture capitalist and government research programs generally have a more favorable attitude towards innovation and new technology, they have stricter conditions and higher costs (Unruh 2000).

2.3.7 Overview of Barriers

Table 2 Overview of barriers to reducing energy used for thermal comfort in buildings

Type of Barrier	Identified Barriers
Physiological/ Behavioural	Thermal requirement of building occupants
Economic	Subsidies for energy efficient design
	Expected future prices
	Access to capital for investment in energy efficient technology
	Motivation to invest (percentage of total expenditure spent on energy)
	Transaction costs
	Internalisation of externalities of energy use
	Energy subsidies
	Upfront cost of energy efficient technology compared to conventional technology
	Principal-agent split
Economic/ Institutional	Lending practices of financial institutions
Informational	Information about application/ method of use
	Awareness of advantages
	Formal training in energy efficient design
	Informal training in energy efficient design
Institutional	Level of detail in energy bills
	Priority /interest in energy efficient design
	Enforcement of government policies
	Level of corruption
	Linear, sequential design process
	Traditional contracting practices
Institutional/ Cultural	Level of coordination and trust between industry partners
Regulatory	Polices on energy efficient design
	Policy on investment in energy efficient design
	policy on procurement of energy efficient design technologies

Of these, the main reasons for the poor implementation of energy efficiency projects in the Maldives arising from the lack of a coordinated effort at a national level to promote energy conservation activities have been identified as follows (PricewaterhouseCoopers India Pvt. Ltd 2011).

- Lack of policies to regulate energy efficiency and conservation in the different sectors of the economy, and the energy performance standard of equipment (Lack of incentive)

- Lack of awareness of the advantages gained from energy efficiency, among industry players, government and private individuals, coupled with the lack of opportunity for education and training in this area. (Lack of awareness)
- Lack of sufficient financial mechanisms to facilitate investment in energy efficiency (Lack of resources)

3 The Contextual Setting of the Maldives

3.1 *Geography*

The Maldive islands comprise of roughly 1190 islands grouped into 26 natural atolls that are spread over 860km across the Indian Ocean (Ministry of Construction and Environment, 2004). The terrestrial area of the islands amount to only about 300km^2 (1%) of the country's total territory, the rest of which is marine environment (Ministry of Construction and Environment 2004). The islands differ in size and geography, and range from little more than sand banks of 0.5km2 to islands of 5km2, around 80% of which are less than 1m above the sea level (Ministry of Construction and Environment 2004).

3.2 *Climate*

Being a tropical country, Maldives, enjoys year-round sunshine averaging 2744 hours per year. Much of the average annual rainfall of around 1996 mm is received during the southwest monsoon, which lasts from mid-May to November and brings torrential rains. Although the annual temperature range is very slight, the monthly average temperature increases in the northeast monsoon, starting January, and peaks at about 29.4°C in April, but decreases to around 28°C by August and stays constant for the remaining months of the southwest monsoon. The diurnal temperature range varies from 31°C during the day to 23°C at night (Maldives Meteorological Service 2010). The relative humidity ranges between 73 and 85% (Ministry of Construction and Environment 2004). The Maldives, with relative humidity greater than 50% and average annual temperature higher than 23°C, can be classified as a Hot Humid country.

3.3 *Population*

The population of the country recorded in the latest population census of 2006 was 298,916. This figure is projected to have grown to around 330,000 people by 2012, and is expected to reach 370,000 by 2020. Although the national population growth rate was about 1.69%, the rate of growth in Male' was much higher at 5.7%, while that of rural atolls was negative 0.8%, due to internal migration/ urbanisation of the population from 1995 onwards (Ministry of Planning and National Development 2008). This has resulted in 35% of the population residing in Male', making it one of the most densely populated cities. The number of residents in the 2km^2 island of Male' alone, including expatriates is expected to be more than 150,000 (Male' City Council Idhaaraa [n.d.]).

The local government has recently embarked upon a program to alleviate the housing condition of the urban population, called the Veshi Fahi Male' program, which includes the development of 3000 housing units in the Greater Male' Area, which includes Male', Villigili, Hulhumale' and Gulhi Falhu islands (Male' City Council Idhaaraa, [n.d.]). Construction of a further 7000 housing units on different rural islands are in different stages on completion.

3.4 Energy Supply

The Maldives is almost entirely dependent on imported fossil fuels for its energy needs. Over 99% of the total energy supply for the country in 2009 (comprising of diesel, petrol, Jet A1 fuel, LPG and kerosene) was imported. Diesel is mainly used for marine transport and conversion to electricity, while petrol is used for land and marine transport. LPG is predominantly used for cooking, although some amount of kerosene and biomass is also used for domestic purposes, mostly in rural areas (Riyan Pte Ltd 2010).

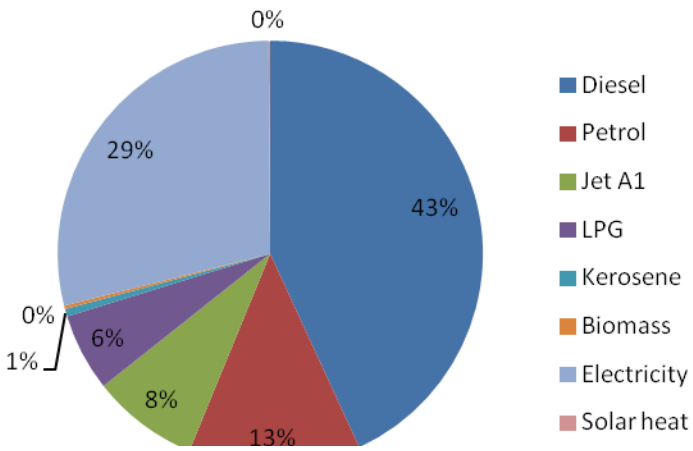


Figure 2 Share of Different Final Energy Sources in Total Energy Consumption (Adapted from Riyan Pte Ltd 2010)

3.5 Energy Consumption

As a country with a widely dispersed geography of groups of islands separated by oceans, a large amount of energy is required for transportation. A significant amount of energy is also consumed by fishing and tourism industries, as the two main economic sectors. Residential, commercial and public buildings (excluding tourist resorts) consume about 28% of the total energy used in the country, with residential buildings accounting for almost 19% (Riyan Pte Ltd 2010).

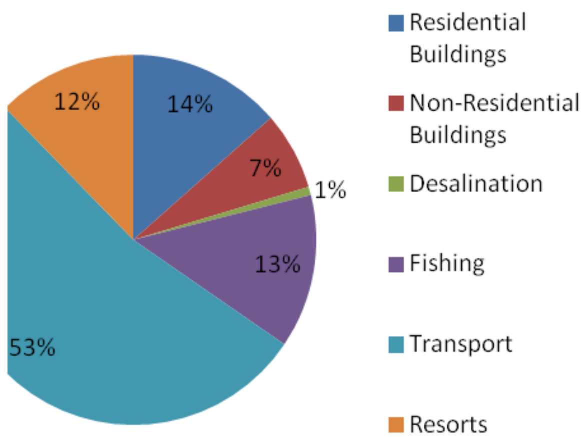


Figure 3 Energy Consumption by Sector (Adapted from Riyan Pte Ltd 2010)

Over 50% of the energy consumed within buildings is consumed as electricity. LPG and some amount of biomass and kerosene are also used, mainly for cooking.

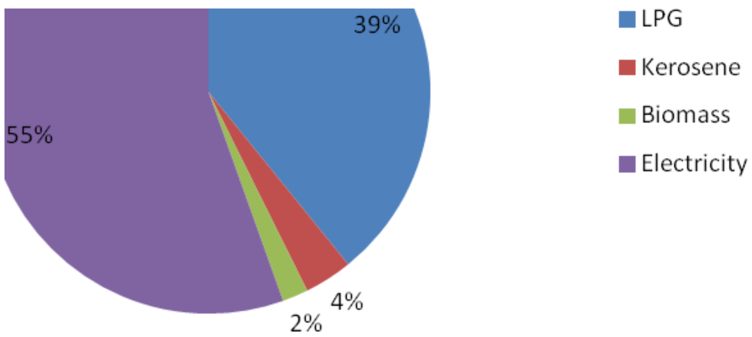


Figure 4 Share of Different Final Energy Sources in Total Energy Consumption in Buildings (Adapted from Riyan Pte Ltd 2010)

While a detailed study of end uses in buildings have not been carried out, a preliminary analysis of end uses in residential buildings in Male' in 2004 indicate that Thermal Comfort requires a significant share of electricity in buildings (PricewaterhouseCoopers India Pvt. Ltd 2011).

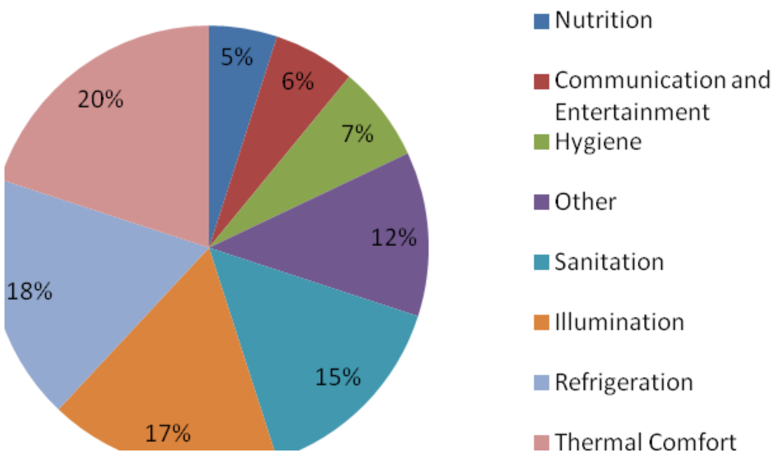


Figure 5 Share of Different End Uses in Final Energy Consumption in Urban Residential Buildings (Adapted from PricewaterhouseCoopers India Pvt. Ltd, 2011)

The increase in ownership of air conditioners over the recent years would have increased the amount of electricity used for space cooling, especially in the densely populated urban environment of Male'. 60% of urban households now own air conditioner (Department of National Planning 2012), compared to just 17% in 2006 (Ministry of Planning and National Development 2008).

Of the approximately 58MW of installed capacity in the inhabited islands of the Maldives, about 38MW is in Male', while a further 51MW is installed in resort islands (Nashid 2011). The relative amount of energy consumed by residential buildings is lower in rural areas (Figure 6) as is the specific energy consumption (1658 kWh/capita and 720 kWh/capita in urban and rural areas respectively).

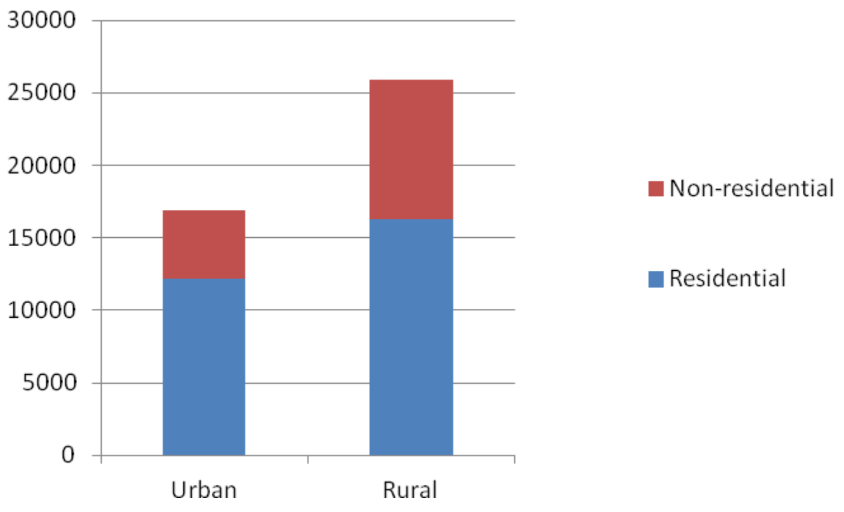


Figure 6 Energy Consumption in Residential and Non-residential buildings in the urban Male' and other rural islands (Adapted from Riyan Pte Ltd 2010)

3.6 Energy-related Policies and National Plans

The **National Energy Policy** of the country, developed in 2010, sets out eight major objectives aimed at enhancing the reliability of and access to energy services by the entire population, increasing the use of local and renewable energy sources, improving energy efficiency and conservation, and strengthening the institutional capacity and quality of energy services. Furthermore, it establishes the target of achieving carbon neutrality in the energy sector by the year 2020 (Ministry of Housing and Environment 2010).

The recently drafted **Maldives Energy Bill 2010** mandates the establishment of a renewable energy unit and a National Energy Efficiency Division within the existing Energy Department of the Ministry of Housing and Environment (PricewaterhouseCoopers India Pvt. Ltd, 2011), underlining the acknowledgment of the need for adoption of renewable energy and increased energy efficiency, within the framework of a sustainable energy policy.

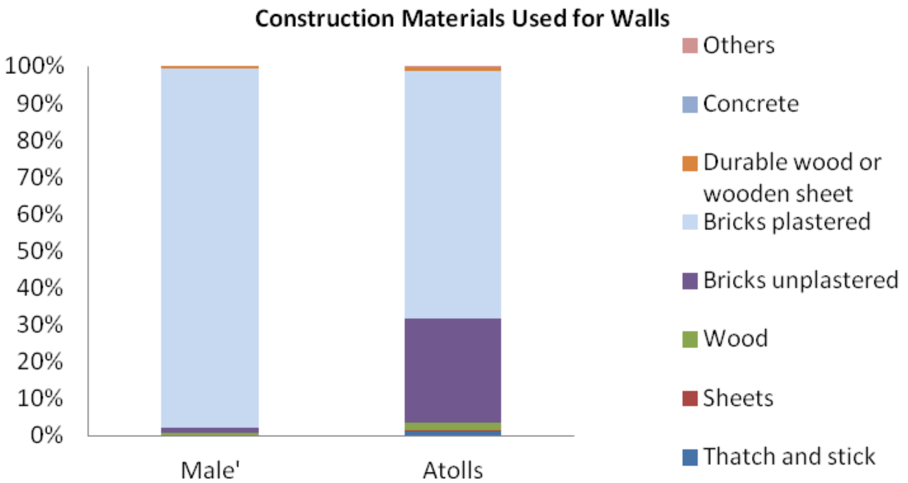
The two major schemes/ plans related to the energy sector are the Renewable Energy Technology Development and Application Project (**REDTAP**) and the Strengthening Maldivian Initiatives for a Long Term Energy Strategy (**SMILES**) project. The goal of REDTAP is "the growth rate of greenhouse gas emissions from fossil-fuel-using activities, such as power generation and process/water heating, is reduced through the removal of the major barriers to the development and application of renewable energy (RE)-based systems that can supplant part of the fossil fuel use in the Maldives" (van den Akker and Saleem 2007, 4). While the main aim of the SMILES project is support government initiatives to develop a sustainable energy policy by taking into account the demand and supply side energy management strategies, the focus is to replace conventional fossil fuels with local renewable energy sources (PricewaterhouseCoopers India Pvt. Ltd 2011).

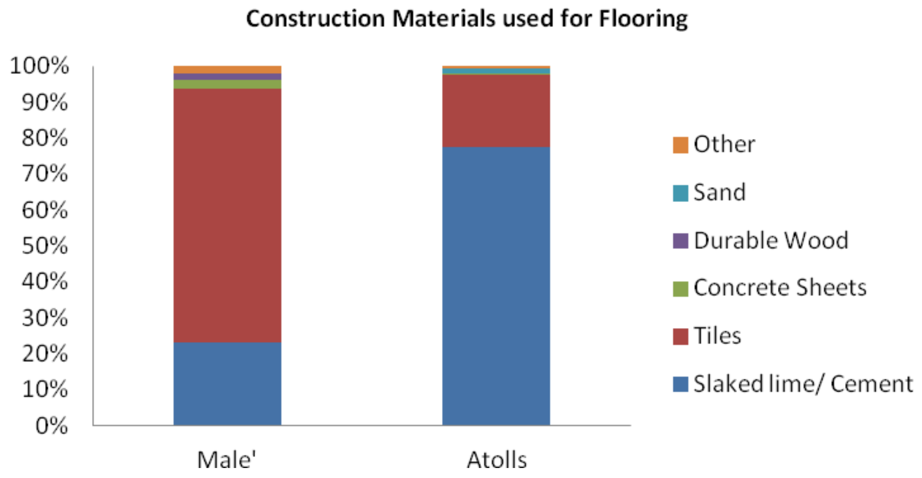
Several renewable energy projects have already been initiated, including solar PV installations of about 130kWp and wind power installations of about 104.2kW, between 2006 and 2011. A further 63MW of electricity is planned to be generated in various parts of the country using solar PV and wind power (Nashid 2011). While localised renewable energy projects in small rural islands is showing promising potential, the situation in Male' is more complicated. It has been suggested that meeting the demand for energy in Male' using renewable energy sources may not be possible with today's technology (especially in storage devices), given the unpredictable nature of the wind resource and space limitations for solar PV installations in the crowded urban environment. The roof area: volume ratio of the mostly multi-storeyed buildings in Male' may be insufficient to provide for the entire building's energy demand, especially as many roofs are mounted with outdoor components of air conditioning units, etc. and the buildings tend to get shaded over by other buildings.

However, energy efficiency has not been given equal emphasis in the current energy-related initiatives. The Maldives National Building Code Handbook includes Energy Efficiency as one of the major components. According to this, buildings are required to have provision for ensuring energy efficiency in controlling the indoor temperature, if the energy is provided by the public electricity supply or a depletable energy source (Ministry of Construction and Public Infrastructure 2008). However, the Compliance Documents that provide details for the conditions that would need to be met in order for a building to be compliant with the Building Code needs to be prepared by the Maldives Energy Authority, and is yet to be developed. In the absence of this document, verification of compliance with the requirements of the code is not possible. Use of energy efficient equipment is also hampered by the lack of a policy that determines the required energy performance for equipment, most of which are imported (PricewaterhouseCoopers India Pvt. Ltd 2011).

3.7 Building Stock

Like most hot humid tropical countries (Baker 1987), coconut palm thatch was traditionally a prominent feature in Maldivian buildings, as a material for both roofs and walls. However, corrugated metal sheets and cement blocks have slowly replaced thatch walls and roofs. The transition to walls of mostly cement blocks was preceded by an era where the use of coral stone was widespread as a construction material. However, the banning of coral mining and the widespread availability of imported construction material has led to the widespread adoption of cement blocks as the major material used in constructing walls. Figure 7 shows the major material used for constructing Maldivian buildings, according to the 2006 population and housing census.





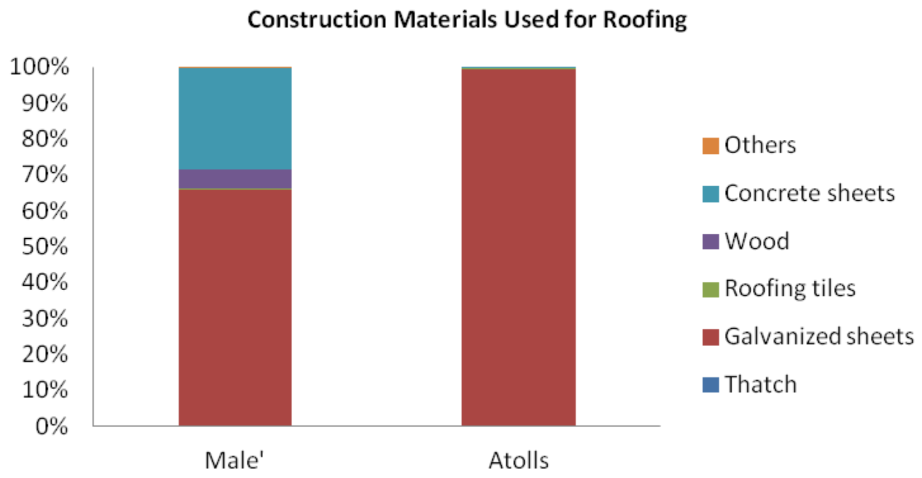


Figure 7 Construction Materials used in Maldivian Buildings (Adapted from Ministry of Planning and National Development 2008)

The building sector in the Maldives is dominated mostly by residential buildings, especially in rural areas where secondary and tertiary economic activities are minimal. Commercial buildings are mostly limited to Male' and some of the major population centres in rural areas, where commercial activities are concentrated. While high-rise buildings are now the norm in urban Male', single-storied houses are still prevalent in rural areas. However, data on the exact number or ratio of residential and non-residential building is not currently available, much less the floor area.

3.8 Building Sector Regulation

The construction industry is regulated by the Ministry of Housing and Environment, with the Maldives National Building Code as the main document that specifies the recommended best practices for buildings of the Maldives (Ministry of Construction and Public Infrastructure 2008). Designed as a performance-based code, it defines objectives to be met, rather than stipulate specific designs or products. However, the effectiveness of the building code is limited in the absence of Compliance Documents, which determine whether a building complies with the building code, and laws and regulations to give the building code legal standing. Compliance Documents are being developed for each of the technical clauses included in the building code handbook, in consultation with relevant authorities. The Compliance Documents for the Energy Efficiency clause is being developed in consultation with the Maldives Energy Authority (Hameed, pers comm.). The draft National Building Act is currently undergoing revisions following which they will be submitted to the parliament (Shaufa, pers comm.).

Currently, the design and construction of single storey buildings does not require approval from authorities while the design of buildings with two or more storeys have to be evaluated and approved by licensed structural engineers prior to construction. The maximum building height allowable is determined based on the plot size. Ventilation is also required for every room, and the size of openings is determined based on the floor area of the room. As buildings are usually located immediately adjacent to surrounding buildings, especially in the congested urban city, this requires ventilated spaces to be designed within the building, to provide ventilation to all rooms, most of which are double (or more) banked. Although building design is checked for structural integrity and other requirements (e.g. ventilation) and compliance is monitored prior to inhabitation, before building services such as electricity and water are provided in the urban city, renovations are not strictly monitored or regulated (Naufal pers comm.).

4 Research Methodology

The study included three main stages. The first and third stages required desk studies, while the second stage consisted of field research.

4.1 Development of Research Framework

The theoretical and methodological frameworks of the study were determined in the first stage. The main aim was two-fold: to develop a framework that could be used to identify the specific design features that could enhance thermal comfort in the Maldivian building stock, and to identify the factors that could limit the amount of energy savings achieved from improved building design.

The amount of energy savings achieved from improved building design could be limited, either because of factors that limit the adoption of such energy efficient technology (level of adoption), or because the full potential of adopting the technology is not realised (success of adoption).

The design features that enhance thermal comfort in tropical buildings, and the factors that could limit both the level and success of adoption of energy efficient technology in building design, were identified in the initial stage of the research, based on extensive literature review. A theoretical framework for analysing and linking the identified factors that affect energy use was developed.

The current situation with regard to building design and energy use for thermal comfort, as well as occupant characteristics which affect the level of energy savings achievable, were identified by means of case studies of six different building types that represents the building stock of the Maldives.

The ideal case for energy efficiency was determined for the identified factors, to determine opportunities for energy savings by means of improved building design. This was further verified through consultation with local architects and building energy experts.

The case studies were also used to determine barriers related to building occupants that limit their ability to reduce energy consumption for thermal comfort. Barriers pertaining to the building industry, financial institutions and government institutions, as well as technical constraints related to building design were identified by means of semi-structured interviews with relevant individuals and organisational representatives.

The objective data obtained from the case studies, and the subjective data gathered from case studies and interviews, were analysed in order to determine the opportunities and barriers to improving energy performance (related to thermal comfort) through improved building design.

4.2 Initial Desk Study

The theoretical framework for the study, with regard to opportunities for improving thermal comfort through building design, and barriers to achieving energy savings through improved building design, was developed in the first stage of the study. Literature related to building design, especially in the tropical warm, humid climate, was reviewed. Special attention was given to find literature on tropical islands, as the island environment is different from other tropical regions.

Architects and relevant public officials were interviewed to get a preliminary idea of design elements common in the Maldives' building stock, and opportunities to reduce energy demand passively. As the initial desk study and interviews with architects made apparent the widespread use of air conditioners in the urban buildings, and the huge inefficiencies in energy use related to air conditioners, aspects related to air conditioner efficiency were also included in the field studies.

4.3 Case Study

The second stage was aimed at determining the state of Maldivian building stock, with regard to the identified factors that affect energy use in buildings. This was done by means of case studies of each of the six building types. The building types chosen to be included are common building types in the Maldivian residential and commercial building stock. The selected building types are:

- Urban Residential Multi-family
- Urban Commercial Office
- Urban Commercial Restaurant
- Rural Residential Single-family
- Rural Commercial Office
- Rural Commercial Restaurant

4.3.1 Case Study Methodology

Case study as a research strategy is used to gain an in-depth understanding of the context of a phenomenon, without necessarily (but possibly) defining its elements and relationships in advance, using the case study methodology (Cavaye 1996). The case study methodology involves using qualitative data collection and analysis methods (although quantitative methods can also be used) in the natural context of the phenomenon without explicitly controlling the variables (Cavaye 1996). The phenomenon to be studied in this study is energy use for providing thermal comfort, which is affected by several different factors, such as climate, building and urban design, behavioural characteristics of occupants, etc. The case study research has two distinct aims- to determine the building design features, thermal requirement of occupants and thermal environment in the building; and to identify the cultural/ behavioural factors that alter the thermal requirements of occupants in the Maldives and constraints to improving thermal comfort using building design features and behavioural adaptations.

Case study research can take various forms, based on epistemology, research objective, research method and research design. In this study, a positivistic approach is taken with regard to the building energy use and design features, thermal requirement of occupants and thermal environment in the building, since the components that determine these elements are identified a priori and the theoretical framework has been developed, based on literature (Cavaye 1996). However, an interpretative approach is taken with regard to the culturally determined factors that influence thermal comfort in buildings, as the theoretical constructs have not been determined beforehand, and the context of the phenomenon is investigated explicitly (Cavaye 1996).

The research study may be used to describe phenomena, test theory, and/or develop theory (Cavaye 1996). In this study, the case studies are used to describe the phenomenon with regard to energy use and design features of buildings, the thermal requirement of occupants and the thermal environment in the building. On the other hand, it is used to develop the theory on how context-specific cultural factors affect energy use in buildings, by studying the behavioural adaptations of occupants and the cultural constraints to enhancing thermal comfort.

Multiple cases are used in this study, instead of a single case. Using multiple cases allows cross-case comparisons, and the use of theoretical replication. The case investigated in this study is the building.

The cases studied were selected based on the following criteria:

- Architectural/ design features and occupancy patterns typical of the specific building type, in the Maldives

- Data on design features available
- Respondents cooperative

All surveys were conducted in the natural context, while the respondents were engaged in their normal routine of activity.

4.3.2 Elements Investigated and Method Used

4.3.2.1 Building design features

Typical design features of the existing Maldivian building stock that can influence the thermal conditions of the building interior were determined based on the buildings chosen as case studies, for each building type. Features influencing heat gain to the building and heat loss from the building were studied. These included the building orientation, layout and form; and characteristics of the walls, roof, floor, windows/ opening and internal and external shadings. The construction materials used, colour and finish of the building envelope components and presence of roof insulation were studied to determine the potential for heat gain through the envelope. The building orientation as well as position and location of shadings were studied to determine the exposure to incident radiation and prevailing winds. The presence and type of ventilation was also examined, to determine the potential for heat loss from the buildings. The presence of wall insulation, airtight windows and the position of the outdoor unit of the air conditioner (related to ventilation, shade and distance from indoor unit/ length of the hose) were also studied, as they pertain to inefficiencies in air conditioner use.

4.3.2.2 Thermal environment in the building

The thermal performance of the building was investigated by measuring the indoor environmental parameters that determine thermal comfort. The parameters measured are *air temperature, mean radiant temperature, relative humidity* and *wind speed*. Indoor environmental parameters were measured on site, using portable instruments. The Extech

HT30 Heat Stress WBGT Meter was used to measure Air temperature, Mean Radiant Temperature and Relative Humidity. The EA-3010U Handheld Anemometer from La Crosse Technology was used to measure the average and maximum wind speeds. The Air Temperature measurements were accurate to 1°C, with a range of 0°C to 50°C. Globe temperature (Mean Radiant Temperature) was accurate to + 2°C between 0 and 80°C. Relative Humidity had an accuracy of $\pm$ 3%, between 1 and 100%. Only wind speeds greater than 0.2m/s could be measured accurately.

Measurements were taken within the occupied zone of the building, at a height of 0.6m for seated occupants and 1.1m for standing occupants, according to the measurement protocol in the ASHRAE Standard. The number of measurements of environmental parameters corresponds to the number of occupants surveyed in each building.

4.3.2.3 Occupant Characteristics

The thermal requirement of the occupants was determined based on a subjective survey of the building occupants. The ASHRAE 7-point scale for thermal sensation vote (TSV) and the McIntyre 3-point scale for thermal preference (TP) were used. Both subjective and objective data was obtained while the occupants were involved in their usual activities. In order to maintain the occupant's metabolic rate at the same level throughout the study (Feriadi and Wong 2004), it was ensured that the activity had been continuing for 30 minutes prior to the survey, and continued throughout the measurement period.

The metabolic rate and clothing insulation level of the occupants were estimated using the metabolic rates and insulation levels for typical activities and clothing ensembles given in the ASHRAE Standard, based on observation of occupants' activity level and clothing. This was used together with the measured environmental parameters to determine the PMV according to the ASHRAE Standard, and compare it with the subjective TSV results. Metabolic rate was measured in met units (1 met unit = 60 W/m2 = 18 BTU/h.ft2), and clothing insulation was measured in clo units (1 clo = 0.155 m2 °C/W =0.88 ft2·h·°F/Btu).

The occupants were also asked about the adaptive strategies they use in response to thermal discomfort. Common adaptive behaviours were identified from relevant literature, and the frequencies with which survey respondents adopt the identified adaptive behaviour were determined, using a 5-point scale. An option for specifying other adaptive behaviours that respondents engage in, but not listed in the questionnaire was also provided.

4.3.2.4 Constraints to improved adaptive behaviour

For each of the identified design features and occupants' behavioural factors that influence thermal comfort, the best option for enhancing thermal comfort was identified. Constraints to adopting them were investigated using interviews with architects and building occupants. Building occupants were asked about the factors that prevent or limit their ability to adopt adaptive strategies that enhance thermal comfort passively and thereby reduce energy consumption for thermal comfort.

4.3.3 Study Sites

The studies were conducted in two islands, one urban and one rural. The urban island is the $2km^2$ capital island Male', where about a third of the population and most of the commercial activity (outside tourist resorts) is concentrated. The rural island is the $0.67km^2$ island of Mulah, populated by 1160 people (Ministry of Planning and National Development 2008). All studies were conducted between 12pm and 2pm.

One residential building and two commercial buildings were studied on each island. A single-family home was studied in Mulah, while a multi-family building was studied in Male', as these represent the two different types of buildings common to rural and urban areas respectively. An office building and a restaurant were also studied in both the urban and the rural settings.

The single-family house in rural Mulah is a single storey building consisting of a main building with four bedrooms, a living area and a bathroom, and a separate kitchen and dining area at the back of the house. The kitchen and dining area is separated from the main building by a compound, as is typical for rural residential buildings. The open-air bathroom, located adjacent to the main building, is also typical of rural and traditional buildings in the country. A separate room was later constructed within the compound, as the household size increased, requiring more loving space. Hence, this residential building reflects the phenomena identified as common in the island, whereby rooms are added to the building as the floor space requirement increases. The house is occupied by a single family, which owns the building. The house was studied over two days, from 17 May 2012 to 18 May 2012.

The multi-family building in urban Male' is a five-storey building, with an apartment of three bedrooms, two bathrooms, a kitchen and a living/ dining area on each floor (except for the top floor, where the living area is replaced by an open terrace). Each apartment is rented by a family, except the top floor, which is occupied by the building owner and family. The multifamily building was studied over two days; 26 April 2012 and 1 May 2012.

The restaurant in the urban island is a four-storey building, with open-air areas on each of the two restaurant floors, in addition to the top floor terrace. Half of the open-air space on the ground floor used fans for natural ventilation. Air-conditioned dining areas were located on the ground and first floors, which also had attached kitchens. Two rooms for office work and a pastry kitchen were located on the second floor, while the entire top floor was occupied the open-air terrace. Hence, there was no roof covering the structure. The restaurant was studied on 12 May 2012.

The restaurant in the rural island is a single-storey structure, consisting of a kitchen area, storeroom, counter and an open compound, surrounded by low walls. The open compound contains the seating area, which is divided into two long roofed areas and three smaller separate dining tables. Mechanical ventilation by fan is used at the cashier's counter, the two longer seating areas, and one separate table. The remaining tables are naturally ventilated, while an exhaust fan is installed in the kitchen. The restaurant was studied on 16 May 2012.

The urban office was located on the first floor of a four-storey commercial building (which itself contained a show room, offices and a restaurant). The office space studied consisted of a meeting room, a small cabin, a small pantry and a workspace separated into cubicles via internal partitions. The small office was the headquarters of a local business group. The urban office was studied on 23 April 2012.

The rural office was the island's branch of the national postal service, and was sufficiently small to provide for the needs of the relatively small island population. The office consisted of a work area and a seating area for customers, all in one workspace, with a separate washroom as the only area separated by internal partitions. The rural office was studied on 16 May 2012.

4.4 Interviews

Interviews were carried out with the pertinent parties to determine the relevance of the identified common barriers that limit the reduction of energy use for thermal comfort to the Maldivian context, and to identify additional barriers specific to the country. Table 3 below indicates the identified barriers and the relevant parties who were questioned regarding each. Thermal requirement was determined by analysing the subjective responses of occupants of the case study buildings (thermal sensation vote and thermal preference) as well as the objective calculation of the predicted mean vote (PMV).

Table 3 Identified barriers and relevant interviewees

Identified Barriers	Relevant Interviewee
Expected future prices	
Information about application/ method of use	
Awareness of advantages	
Access to capital for investment in energy efficient technology/ Lending practices of financial institutions	
Motivation to invest (percentage of total expenditure spent on energy)	Client
Transaction costs	
Internalisation of externalities of energy use	Energy service provider
Level of detail in energy bills	
Energy subsidies	
Priority /interest in energy efficient design	
polices on energy efficient design	
Enforcement of government policies	
Level of corruption	
Policy on investment in energy efficient design	
policy on procurement of energy efficient design technologies	Government
subsidies for energy efficient design	
Upfront cost of energy efficient technology compared to conventional technology	
Linear, sequential design process	
Level of coordination and trust between industry partners	
Traditional contracting practices	
Formal training in energy efficient design	
Informal training in energy efficient design	Industry
Principal-agent split	
Thermal requirement	Occupant

The extent of the principal-agent split was determined using published statistics on the number of rented and owner-occupied households. The ‘client’ may or may not refer to the occupant of the building, depending on whether the building is rented or not.

Constraints to improving building design to enhance thermal comfort passively and thereby save energy were determined from interviews with architects, mainly with regard to physical limitations and other design considerations that prevent prioritisation of design for enhancing thermal comfort. An air conditioning professional was interviewed to gain insight into potential inefficiencies as well as the situation regarding such, in the urban buildings.. As most of the architects responded to a survey anonymously over the internet/ via email, they are not listed.

4.5 Data Analysis

The operative temperature (T_{op}) PMV and PPD were calculated using a computer program, provided in the ASHRAE Standard. The calculated PMV was compared with the mean actual TSV, in order to determine how significant adaptive strategies were in altering the thermal requirements of the occupants.

The effectiveness of current design features in providing adequate thermal comfort to occupants of the building studied was determined by comparing the neutral temperature (T_n) with the mean operative temperature (T_{op}) in the buildings surveyed. Linear regression of operative temperature (T_{op}) against the TSV was analysed to determine the neutral temperature, which was taken to be the intercept of the linear regression, according to Feriadi and Wong (2004).

The design of the case study buildings were analysed to determine if the features identified presented opportunities for improvement in terms of thermal performance. The type and frequency of adaptive strategies used by occupants was determined based on interviewees’ responses. Differences between urban and rural, as well as residential and commercial buildings were analysed. Qualitative analysis of the semi-structured interviews was used to identify and assess the common constraints to adopting energy efficient building design as well as the economic and institutional barriers to reducing energy demand for thermal comfort through energy efficient building design. The identified barriers were analysed and reclassified, so as to develop a strategy to address them, given the existing economic, political and social factors.

4.6 Research Validation

Focused interviews with experts were used to verify observations and gather additional information regarding specific aspects such as air conditioner use, planned government policies on energy efficiency and the feasibility and effectiveness of different building design features.

Although case studies cannot be used for statistical generalisation, and the results obtained from the case studies cannot be generalised to the building stock of the country, it is useful for gaining a detailed understanding of the cases that were studied. Since this study utilised multiple case study buildings, they can be compared and a generalised understanding of the barriers to adopting better design features and occupant behaviours could be developed, through meta analysis of the results (Ford et al. 2010).

5 Results and Discussion

5.1 Existing Characteristics

5.1.1 Design Features

Orientation

The orientation of the buildings studied depended entirely on the orientation of the plot, determined by the urban design. Due to the small size of the plot, orientation could not be changed based on the need to minimise solar heat gain or maximise access to natural breeze.

Layout

The layout of rural residential building was designed in such a way that minimises heat gain from heat generating rooms (kitchen area) to the main living quarters. The separate kitchen is a common feature in traditional houses. However, increasing demand for land appears to be forcing residents to construct attached kitchens.

Another feature regarding the building form of the rural residential building is the sequential nature of construction; rooms had been added to the original building, as needed when demand arose and the financial situation of the occupants allowed. Hence, a bedroom had been added within the compound of the original building, nearer to the kitchen. This was identified as a common occurrence in the island (Adam, pers comm.).

The layout of the urban residential building is such that the main living areas are at the front of the building, facing the road. The kitchen is situated in the middle, between two ventilation spaces within the building. This layout minimises exposure of the bedrooms to direct solar radiation, and maximises the air movement within the living areas and the kitchen, which presumably require less privacy than bedrooms, and can therefore be ventilated in the dense urban environment via openings.

The layout of the offices, being single purpose rooms, was not of great importance, especially as large heat-generating equipment were not being used therein. However, the kitchens of the restaurants were major heat generating areas. Being commercial buildings, the function of the restaurants required the dining area to be at the front, and the kitchen at the back. In both cases, the cashier’s counter separated the kitchen from the main dining area, limiting the heat transfer to the area that is required to be kept cool the most.

Walls

The external walls of all the buildings studied, except for most parts of the rural residential building and the urban office, were of cement blocks, and were plastered with cement. The main building of the rural residential house was of coral stone, plastered with cement, while the more recent additions were of plastered cement blocks. The external facade of the urban office was made of reflective aluminium cladding. The walls of all buildings were painted with mostly light colours, and did not have reflective finishes.

The urban residential building and restaurant, and the rural office, were surrounded by buildings on three sides and was exposed only on the side facing the road. The urban office, being situated as it was on a corner, was adjacent to two buildings and exposed to the road on two sides. The main building of the rural residential building was adjacent to two surrounding buildings on two opposite sides, and the sides facing the road and the backyard of the adjacent house at the back were exposed. The rural restaurant was also located on a corner, with three sides exposed to the road and one side adjacent to a building.

Roof

Roofs of five of the buildings studied consisted of corrugated metal sheets, with coconut palm thatch used in the dining area of the rural restaurant. Although thatch was traditionally used in the construction of both walls and roofs, it is now used mostly for decorative and aesthetic rather than practical purposes. The metal sheets have reflective finishes, but rusting is common and this reduces the reflectivity of the roof, increasing the heat gain (Baker, 1987). Furthermore, the material tends to have low thermal resistance (high conductivity), allowing indoor temperatures to rise rapidly during the day, and decrease rapidly during when outdoor temperatures drop.

However, this effect may be minimised by using ceilings for insulation (Baker 1987). Ceilings were present in most of the buildings studied, except for some parts of the rural residential building (where the older constructions did not feature ceilings, while the more recent additions to the building had ceiling insulation installed). Although ventilated roof voids can be highly effective in removing heat gained by the roof (Baker 1987), these were not present in any of the buildings studied.

Floor

Ceramic tiles are the most common material used on floors. The rural residential building also had areas with concrete slabs, some of which were covered with linoleum. The rural restaurant had floors of concrete slabs in the main area, and coarse white sand in the separate dining spaces.

Windows and Openings

It was observed that the use of windows for ventilation (as opposed to day lighting purposes) was not common in any of the buildings studied. In the urban buildings, this was mainly because of the use of air conditioners. Large french windows were located at the front of the apartment (north facade, facing the road) in the urban residential building, with smaller windows on the eastern facade. While windows were also present in all the rooms, opening to ventilation spaces within the building, most were not used due to the use of air conditioners. The windows in the kitchen, however, were observed to be open.

The rural residential building did not appear to be designed with ventilation needs in mind, presumably because rural residents commonly seek the benefit of the natural breeze from outdoor spaces. Window in the external facade were observed only in the main living room, one (separate) bedroom and the dining room. However, these were also commonly observed to be closed. Windows were also observed in the internal partitions of the bedrooms, opening to the corridors in the main building. However, these too were kept closed, for privacy and convenience. The lack of windows may also be attributable to the fact that houses, both in urban and increasingly in rural areas, often share external walls with the adjacent houses, so that buildings are open to the road on one side and to the back or side yard on the other, where present (mostly in rural buildings). Hence, windows cannot be placed on the two facades that are shared with other buildings.

The rural restaurant had low walls, admitting the natural breeze from two sides. The rural office building appeared to depend entirely on fans for mechanical air movement, with the door of the building reportedly kept open, allowing exchange of air with the outside.

The air-conditioned rooms (urban office and restaurant, and some of the rooms in the urban residential building) did not keep any openings (windows, required by law, were kept closed). Cross ventilation and displacement ventilation were therefore not possible in these rooms. The living rooms and one of the bedrooms in the non air-conditioned parts of the urban residential apartments did have the possibility for cross ventilation, with openings on opposite walls. However, two of the rooms in the urban apartments had only one window, and so could not create a draught via cross ventilation or displacement ventilation.

The rural residential building also appeared not to use windows for ventilation, as they were mostly kept closed. However, the main door was kept open to admit the breeze. Since doors were located on two opposite sides, with a corridor joining the two, a draught could be created, creating air movement within the occupied space. This type of openings on opposite sides of the building, is a feature of rural architecture, and can help increase heat loss to the environment via cross ventilation especially if in approximately the north-south direction, due to the direction of the prevailing winds in the two monsoons.

Openings for displacement ventilation were not observed in any of the buildings studies. However, small openings/ slits in the wall above the door in the rural residential building suggest that displacement ventilation via the stack effect was important in the traditional building design. These slits are a feature of traditional architecture, but are not common in modern buildings.

Shading Devices

Internal shading was used in residential and office buildings in both the urban and rural islands. Cotton curtains with different patterns were used for this purpose in residential buildings and the rural office building had purple cotton curtains. White blinds were used in the urban office building. No internal shading was used in either of the restaurant buildings.

Roof overhangs were common in the rural buildings, but not in the urban buildings. Instead, the urban residential building featured balconies on the northern facade, while windows of the urban office building were shaded to some extent owing to their being slightly inset from the building facade.

Possible Opportunities for Improvements in Building Design

The orientation of the buildings in the country, especially in the urban areas, is determined by the orientation of the plot, due to the small size of the plots. Therefore, optimising the orientation cannot be achieved at the building level. Urban-scale land use planning is required to align the orientation of the buildings with the optimum orientation for reducing exposure of large areas of the building facades to solar radiation, and maximising access to prevailing winds. However, the layout of the rooms within the building can be designed with their particular functions and occupancy levels, and the resulting effects on heat generation and cooling requirement in mind.

Since orientation cannot easily be changed to reduce exposure of the building envelope to solar radiation, external shading devices can be used to protect important facades from direct solar radiation. It might not be practical to provide shading to the entire facade: instead, adjustable projections can be used to shade the openings such as windows, through which solar radiation can enter directly into the building

The availability of appropriate materials for the building envelope locally is a challenge. On the other hand, simple measures such as painting the external walls with white or light colours that reflect and emit solar radiation are easy, inexpensive and effective, as it can reduce the temperature at peak solar radiation considerably, compared to a dark surface under the same conditions (Bansal *et al*. 1992; Uemoto *et al*. 2010)

Windows in the country tend to be single-glazed. Tinted glass is becoming increasingly common, possibly due to the greater privacy they provide. Tinted glass or heat absorbing glazing seem to offer no effective solutions to reducing cooling demand, as they absorb heat within the glass, which reaches the building interior by conduction and radiation (Gut and Ackerknecht 1993). Window films with thermal properties such as low emissivity films (low E films) may be useful in reducing the amount of heat transfer from the windowpane to the interior through radiation (Baker 1987). Hence, low E films can be very effective in air-conditioned buildings with double glazed windows, especially since they are susceptible to damage by air and water when used with single glazed windows.

Ceilings are common in all recent constructions, and are effective in providing some amount of insulation to the space below. Opening up the void between the roof and the ceiling would allow the movement of air and thereby increase heat loss through convection. Since terraces are common in high-rise buildings in the urban city, and surrounding buildings may block proper ventilation in low rise urban buildings, ventilated roof voids will probably be most effective in rural buildings, which are often single storied, and not placed in too compact a manner. Although most common in naturally ventilated buildings, ventilated roof voids can also be useful in minimising heat gains in air-conditioned buildings as well.

Ventilation is a key to providing thermal comfort in the buildings, and cross ventilation appears to be the most effective way to create an exchange of air between the building interior and exterior (Baker 1987; Gut and Ackerknecht 1993). However, large openings are not desirable, especially in urban environments.

Although cross ventilation is most effective in single-banked rooms, it may still be useful to create an airflow between rooms in double (or more) banked rooms. The relative size of the two openings should also be considered, to manipulate the rate of airflow by creating a pressure gradient. Since privacy is a concern, with regard to openings, it might be useful to have openings higher and/or lower than the eye level. Having two openings at different heights could also help promote ventilation through the stack effect, where the lower openings acts as the inlet for cooler air and the higher opening acts as the outlet for warmer (less dense) air. This type of vertical ventilation can be created with openings on the same wall, and can be useful in spaces where cross ventilation is not possible.

Thermal Environment

Table 4 summarises the thermal environment of the buildings studied, classified according to the type of ventilation used in the different rooms of the building.

The average operative temperature was lower for the urban buildings, mostly due to the use of air conditioners to regulate the air temperature, but probably also due to the higher outdoor temperatures measured in the rural island during the field visit compared to the outdoor temperatures measured during the field visits to urban buildings. The average humidity was also lower in the air-conditioned spaces. The average wind speed was highest in the mechanically ventilated spaces, and lowest in the air-conditioned spaces that did not use fans to create air movement (i.e. the urban office).

Table 4 Average Operative Temperature (°C), Relative Humidity (%) and Wind Speed (m/s) of the six buildings studied, according to the type of ventilation use in the room (A/C- air-conditioned, MV- mechanically ventilated, NV- naturally ventilated).

	Building Type	Room type	Average Operative Temperature (°C)	Average Relative Humidity (%)	Average wind speed (m/s)
Urban	Office	A/C	24.4	37.6	<0.1
	Restaurant	A/C	29.5	42.9	<0.1
		MV	31.9	62.2	0.2
		NV	32.6	60.1	0.1
	MF	A/C	28.5	53.3	0.2
		MV	32.2	59.6	0.3
	All building types		28.2	48.1	0.1
Rural	Office	MV	34.4	55.6	0.4
	Restaurant	MV	34.8	55.6	0.2
	SF	MV	32.0	69.4	0.5
		NV	32.4	70.5	<0.1
	All building types		33.6	61.8	0.2

5.1.2 Thermal Preference

5.1.2.1 PMV

The predicted mean vote was positive in all cases, indicating that the thermal sensation was predicted to be above neutral for all respondents. However, there was a considerable amount of variation between individuals, as the PMV ranged between +0.1 and +3.5.

Similarly, the percentage people dissatisfied (PPD) varied greatly, between 5.2% and 100%. The typical classification for thermal comfort (Class B according to the ASHRAE Standard) specifies a PMV of between +0.5 and -0.5, and PPD of less than 10, as indicative of an acceptable thermal environment. According to these criteria, only the urban office provided a thermally acceptable environment, for the level of metabolic activity and clothing insulation level of the occupants of the building.

The calculated PMV and PPD in the rural buildings is extremely high, with PMV ranging between +2.2 and +3.5, and PPD ranging between 84.9 and 100. Compared to this, the range of PMV in the urban buildings was from +0.1 to +2.6, while the PPD ranged between 5.2 and 95.3. Table 5 shows the average PMV and PPD for the six buildings studied.

Table 5 The average Predicted Mean Vote (PMV) and Percent People Dissatisfied (PPD) for the three case study buildings

	PMV	PPD
Urban Office	+0.3	7. 5
Urban Restaurant	+1.6	54.8
Urban Residential	+ 1.9	68.1
Rural Office	+3.2	99.7
Rural Restaurant	+3.2	99.5
Rural Residential	+2.5	91.9

5.1.2.2 TSV and TP

The reported thermal sensation vote (TSV) was mostly less than the calculated predicted mean vote (PMV), and the difference between the urban and rural building inhabitants was not as marked. The average TSV and TP (thermal preference) of the occupants of the six buildings studied are presented in Table 6.

Table 6 The average Thermal Sensation Vote (TSV) and Thermal Preference (TP) for the six case study buildings

	TSV	TP
Urban Office	-0.6	-0.3
Urban Restaurant	0.4	-0.8
Urban Residential	1.7	-0.9
Rural Office	2. 7	-1
Rural Restaurant	1.6	-1
Rural Residential	2.2	-1

The TSV of rural building occupants was still higher in general than that of the urban building inhabitants. The TSV of rural inhabitant ranged between 0 and +3, while that of urban building occupants ranged between -2 and +3. The TSV reported by urban office occupants also fell below 0, indicating a thermal environment cooler than neutral.

It must be noted, however, that even occupants who reported negative TSV's reported their thermal preference as either 'no change' (meaning the thermal environment was acceptable to them as was), or 'prefer cooler'. Most of the urban office occupants preferred the 'no change' option. All of the rural respondents and most of the urban respondents indicated their thermal preference as ‘prefer cooler’, and none of the respondents selected the choice of ‘prefer warmer’ as their thermal preference.

5.1.2.3 Neutral Temperature

According to the calculated PMV, the neutral temperature for the building occupants was 23.6°C (Figure 8). However, according to the subjective thermal sensation votes (TSV), the neutral temperature was 26.3°C (Figure 9).

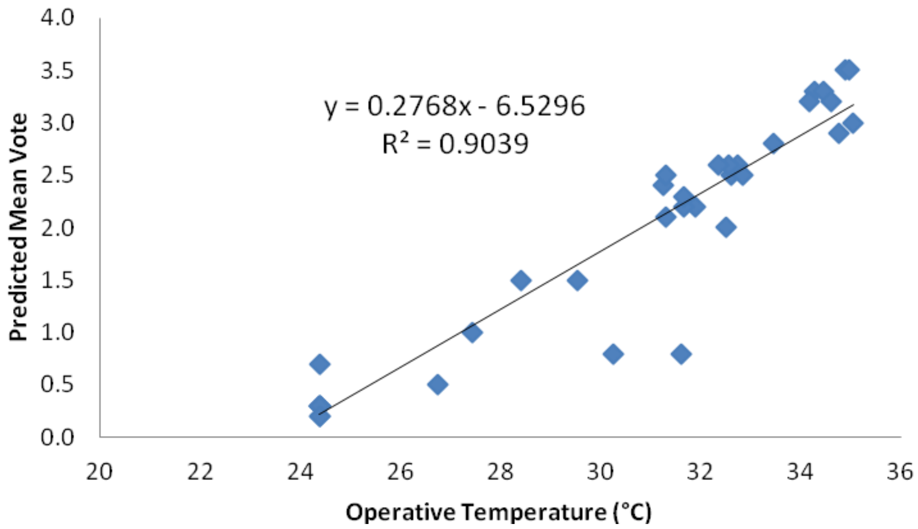


Figure 8 Linear Regression of the Predicted Mean Vote (PMV) against the Operative Temperature in °C

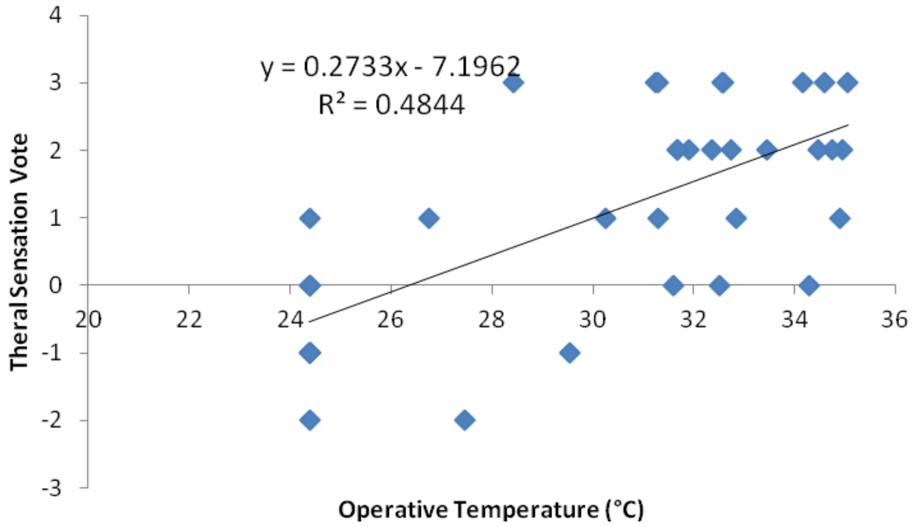


Figure 9 Linear Regression of the Thermal Sensation Vote (TSV) against the Operative Temperature

The difference of 2.7°C between the two neutral temperatures (i.e. the neutral temperature determined based on the TSV and the PMV) indicates the adoption of characteristics on the part of the building occupants that result in their acceptance of temperatures above that predicted by the methodology used for the ASHRAE Standard, as thermally comfortable. Since clothing insulation levels and rate of metabolic activity are taken into account in calculating the PMV, the difference must be explained by other adaptive strategies, including both passive and active adaptive measures.

In both cases, the neutral temperature is below the average operative temperature for the buildings studied. However, the neutral temperature determined based on the TSV was close to the average operative temperature of the air-conditioned rooms studied (which was 26.12°C). This is to be expected, as occupants are able to control the thermal environment to their preference (where the operative temperature is equivalent to the neutral temperature) using air conditioners, which adjusts both the air temperature and the humidity in the air-conditioned space. Hence, the use of air conditioners is likely to be important as an adaptive strategy.

5.1.3 Occupant Characteristics

Clothing type

The clothing insulation value for males in the residential building was quite low, at about 0.30 clo on average. However, that for females was high at about 0.60 clo. This is reflective of the culture, whereby women tend to dress more conservatively, most wearing long sleeved clothing with head covers and long pants. While the head cover is often not used inside the home, the rest of the clothing ensemble tends to be the same (i.e. long sleeves and long bottoms), so the clothing insulation level is high. On the other hand, men tend to dress more casually in the home, often wearing shorts with short-sleeved t-shirts or shirts. Some of the respondents in the studied building were wearing the traditional sarong, '*mundu*', with short-sleeved t-shirts, resulting in very low clothing insulation levels.

The clothing insulation level of office workers was comparatively high, at about 0.60 and 0.62 clo on average for urban and rural office occupants respectively. Most of the office occupants were wearing long sleeved garments with long trousers, as is usual in formal business environments in the country. While government institutions require males to wear neckties, this is not compulsory for most private institutions, as was the case with the studied private office.

The clothing insulation level of restaurant patrons was also quite high compared to the residential occupants, at about 0.56 clo for the urban restaurant patrons. This is probably because the study was conducted around lunchtime, when most of the restaurant patrons are working people on their lunch break. However, some of the respondents were dressed more casually in clothing of lower insulation. This was more the case in the rural restaurant, which was occupied exclusively by males (as is common in public food outlets, especially during the daytime), and the average clothing insulation level was 0.52.

The highest clothing insulation levels on average were observed in the rural residential building. This may be because almost all of the occupants surveyed were females, as was common during the daytime, and the lack of privacy and the more conservative culture in the rural environment compared to the urban environment resulted in greater levels of clothing insulation from garment ensembles featuring long sleeves, long trousers and head covers.

Activity level

Although the proportion of people occupied inside buildings was less in the rural island, due to the observed preference for carrying out domestic activities outdoors, the activity levels among occupants of buildings themselves were similar (and comparatively higher relative to other building types) in both the rural and urban islands, as building occupants were mostly involved with similar activities.

The residential occupants were generally occupied in household activities with high metabolic rates. While some of the respondents were interviewed while they were engaged in their activities, others remained seated for the duration of the interview, so that their metabolic rates were lower. On average, the metabolic rate of both the urban and rural residential respondents was 1.5 met units.

The office inhabitants were occupied with office activities such as typing and reading, which have low metabolic rates. Respondents from the restaurant were also engaged in light activity while seated, except for the restaurant workers who were moving around. Hence, the average metabolic activity level in the urban office and restaurant were 1.1 and 1.2 respectively, while that in the rural office and restaurant were 1.1 and 1.4 respectively.

Passive Adaptive Strategies

Compared to urban areas, rural residents appear to have a greater scope for passive adaptive behaviours to thermal stress, reducing the energy needed to provide thermal comfort. The use of air conditioners is significantly less common in the rural island studied, especially in residential buildings. On the other hand, the use of outdoor spaces for household activities is markedly important in the rural lifestyle. Below are common adaptive strategies listed according to their frequency, as reported by the respondents.

URBAN	RURAL
High fan speed	High fan speed
Drink, Low A/C setting (cooler)	Outdoor spaces, Drink
Low clo clothes	Open windows
Shower, High A/C setting (warmer)	Shower
Outdoor spaces	Low clo clothes
Open windows	Change A/C setting, Low fan speed

The use of windows for ventilation was identified as the least common passive strategy used by urban residential respondents, followed by the use of outdoor spaces. On the other hand, the use of outdoor spaces was the reported as the most commonly used adaptive strategy by rural residents. Although less frequent than using outdoor spaces and drinking, the use of windows was also a common strategy adopted by rural inhabitants, unlike urban inhabitants. Drinking, using clothes of lower insulation values and taking a shower to cool off were identified as adaptive strategies commonly adopted by both urban and rural building occupants.

Some urban residential respondents also identified swimming as an alternative strategy for cooling off. Furthermore, moving around the occupied space was identified as an adaptive strategy for dealing with thermal discomfort by one of the respondents, for instance during blackouts, when fans and air conditioners are not operational. It was also observed that the thermal expectations and understanding of factors that affect thermal comfort is also important in the level of thermal comfort required by different occupants. For instance, high thermal discomfort with excessive sweating was an expected consequence of outdoor activity in the rural environment. Hence, respondents identified use of shade and natural breeze in outdoor (especially coastal) spaces during/ following hard physical work as an important adaptive strategy. Since the thermal discomfort is rightfully understood as a consequence of physical labour, the adaptive strategy aims to adjust the occupants' situation rather than attempt to change the thermal environment by active means.

Active Adaptive Strategies

The two common active adaptive strategies were the use of fans and air conditioners. While fans were used in all the buildings studied, except the urban office building, air conditioners were used only in the urban buildings. However, it must be noted that air conditioners are in fact used in rural islands as well, although to a lesser extent than in urban buildings. Based on interviews with residents, it is apparent that the use of air conditioners in rural islands is also increasing, as the financial capability of the residents improve, making air conditioners more affordable.

The use of fans at high settings was the most common adaptive strategies adopted by both urban and rural occupants. The use of air conditioners was common in urban buildings, since every apartment had an air conditioner in at least one of the bedrooms, and indoor spaces of the office and restaurant buildings were completely air-conditioned. While the fan was almost always kept at the maximum setting, and reducing the fan speed was one of the two least common adaptive strategies in both rural and urban settings, urban occupants reported occasionally increasing the temperature setting of the air conditioner to increase the temperature of their thermal environment.

It was also observed in three of the five air conditioned rooms studied, that the occupants were using fans along with the air conditioners, suggesting that air movement is an important part of thermal comfort for the occupants even when the air temperature is to their preference.

5.1.4 Inefficiencies Related To the Use of Air Conditioners

Since the use of air conditioners was so widespread in the urban buildings, and increasingly becoming more important in rural buildings as well, a professional experienced in installing and servicing air conditioners was interviewed regarding the use of air conditioners and the inefficiencies arising from the way they are installed and used.

Awareness of occupants regarding the choice of air conditioners with the appropriate power rating, efficiency achieved from inverter technology, need for frequent cleaning of filters and matching the fan setting of the air conditioning unit to the temperature setting were identified as important factors in improving efficiency (Bari, pers comm.). Most clients were diligent in taking steps to reduce inefficiencies, once informed. This is likely to be because air conditioners account for a large proportion of the total energy demand from buildings, and improving the energy efficiency of air conditioners is therefore in the financial interest of the building occupants as well.

The role of air conditioning experts in this regard, to educate their clients was noted as critical. However, the lack of experience and knowledge of practitioners was identified as a key barrier, both to increasing client awareness regarding proper use and to installing air conditioning units appropriate for a specific space, in the best position, to maximise efficiency. As the profession is not licensed or regulated, individuals with minimal work experience and knowledge are reportedly free to consult on installation of air conditioners and service them.

The role of architects in designing spaces appropriate for air conditioners was also identified as critical. Although most people are deemed familiar with the efficiency losses due to air leakage from openings to non air-conditioned spaces, leakages from un-insulated doors and windows still occur. Lack of appropriate materials in the local market to insulate doors and windows was identified as the main reason for this, according to the responses from architects. Furthermore, the lack of consideration given to air conditioning needs during the building design process results in the outdoor units of air conditioners having to be placed in constrained spaces such as small ventilation spaces within buildings, or small spaces between buildings, as was the case in the urban residential building studied. This restricts air movement around the outdoor unit, limiting the efficiency with which the thermal conditions of the indoor space are regulated. Many outdoor units of air conditioners are also mounted on roofs, exposing them to direct sunlight, resulting in decreased efficiency as well.

The lack of practical knowledge and experience of architects and designers, as well as the lack of coordination between the design team and building service experts (including electricians, plumbers, etc) was identified as major barriers in constructing energy efficient buildings. Moreover, this resulted in higher costs, as building components have to be changed after construction.

5.2 Constraints to Increasing Energy Efficiency through Building Design

5.2.1 Physical Design Constraints

The major constraint identified by all architects surveyed was the lack of space or small plot size, which limits the feasible design options, as clients want to maximise the usable space. While the congestion in the urban city of Male' is extreme, scarcity of land is also experienced by rural inhabitants, since land is an extremely scarce resource in the country, with a total land area of about 300km^2 (Ministry of Construction and Environment 2004).

Although the space constraint is mostly in reference to the floor area available, height limitations stipulated by the building regulations, which in turn depend on the plot size, also limit the possibility of features such as ventilated roof voids and raised floor systems. Most building owners opt for terraces above the top storey of multi-storey buildings instead of roofs, in order to be able to use the space.

Major design constraints identified also include trade-offs, such as the increased possibility of rain ingress and exposure to high wind speeds, when buildings are designed with large openings oriented towards prevailing winds to increase air movement and thereby increase heat loss from the building interior. However, adjustable shading devices and operable windows can be used to control the exposure of the building interior to the elements. Barriers to designing buildings with sufficient openings to encourage heat loss also include the exposure to dust and noise from the surroundings, and the loss of privacy, especially in congested spaces. On the other hand, some features designed to improve the thermal environment within one building can lead to discomfort in other surrounding buildings. For instance, using reflective materials on building facades can reduce the heat gained by the building envelope, but increase glare and heat gain in surrounding spaces and buildings.

While the thermal properties of construction materials are important in determining the thermal performance of the building, lack of availability of appropriate materials locally was also identified as a barrier to improving the thermal performance of buildings through design. Furthermore, lack of experienced construction workers and lack of familiarity with construction techniques and building components designed to improve the thermal environment of the building is also a major limitation to widespread adoption of such techniques and technologies.

The orientation and location of the building were also identified as important in determining the effectiveness of design features in improving the thermal environment of the building. Utilising prevailing winds to their potential is limited for buildings that are not oriented to prevailing winds, or are shielded from prevailing winds from higher buildings on the windward side of the building. Hence, urban planning was identified as critically important in determining the potential for reducing cooling energy demand using building design, together with occupant behaviour. However, there are several factors that prevent occupants from engaging in behaviour that would limit the energy demand for achieving thermal comfort.

5.2.2 Behavioural Constraints

Privacy concerns and noise were identified as major limitations to adaptive behaviours such as opening windows in urban Male', in addition to pollution and dust. However, this was less of an issue in the rural island of Mulah. While Male' is home to 42105 registered motorised vehicles compared to 2275 vehicles in the rest of the country combined (Bernard *et al.* 2010), the number of motorised vehicles in Mulah is therefore visibly much less, leading to a much more quiet, relatively cleaner environment. Privacy also appeared to be less of a concern in the rural island, where adjacent houses were commonly observed to share low separating walls. However, concern for privacy and security appear to be increasing in importance even in rural areas, as the lifestyle and economic situation of rural residents slowly change and crimes like theft increase.

The high prevalence of air conditioners in urban buildings both precluded the need for and acted as a barrier to open windows, since air conditioners provide the required thermal environment, and its efficiency is reduced when air leaks out of the air conditioned space through openings like windows. Where operable windows were made redundant by the use of air conditioners, windows were observed to be blocked by furniture. The use of windows in offices was also limited by the fact that incoming breeze could disturb items such as paperwork.

The high cost of water was identified as a constraint for urban building occupants to drinking as often as they would like to alleviate thermal discomfort, especially in non-residential buildings. The need to conserve water was also identified as a limitation to bathing as a response to thermal discomfort. Taking showers was also identified as an inconvenient strategy for reducing thermal discomfort, as it is not practical to shower multiple times during a workday, especially considering the busy urban lifestyle.

The use of outdoor spaces was not identified as a common adaptive strategy to thermal discomfort in urban areas, due to the lack of suitable outdoor spaces in the midst of the bustling urban city. The widespread use of air conditioners also precluded the need for outdoor spaces, although the amount of energy required for air conditioning is significantly high. However, the preference for outdoor spaces, if available, even in urban settings, was demonstrated by the preferential seating of urban restaurant patrons in open-air areas, even with seating available in air-conditioned areas. The need for natural breeze and fresh air common in the Maldivian culture was cited as the reason for this preference.

The occupants of residential buildings were generally observed to use low insulation clothing, such as the traditional 'mundu' for males. While most women generally wear head covers outside their homes, they too show a preference to low insulation material clothing, especially inside their own homes. On the other hand, office workers wear mostly long-sleeved shirts with trousers, which have relatively higher insulation values. While this is true, even for private offices in the urban environment, the dress code was less formal in the rural setting, suggesting that the urban professional culture is more restrictive in terms of thermal comfort.

Similarly, it was more often identified as difficult for office workers to control their thermal environment according to their preference despite the use of air conditioning, since there is a variation in individual preferences within the shared space. However, this restriction to thermal comfort due to others' thermal preferences was also identified by urban residential occupants, where a room is shared by two people with very different thermal requirements. This is more apparent in air-conditioned rooms, probably because the deviation of the thermal environment of the conditioned space is greater compared to the ambient condition.

5.2.3 Informational Constraints

According to the architects surveyed, another barrier to incorporating the best design features in terms of their cooling potential was the need for preserving the aesthetics of the building. Features such as openings for vertical ventilation were identified as not aesthetically pleasing, and therefore not desirable, possibly since they are unfamiliar features. Hence, client preferences and level of awareness of clients was identified as an important factor.

All of the architects agreed that clients do not have adequate information regarding the application of the different design features, and how they reduce the cooling energy requirement. Furthermore, they suggest that most clients are not even aware of the advantages of incorporating such elements into the building design, in terms of thermal comfort and financial benefit due to avoided electricity costs. However, most of the clients interviewed seemed to be aware of the advantages of such features in general, though not well informed in the specific application of the different techniques.

Some of the architects highlighted their own responsibility in educating the clients, and making clients aware of the need for and advantages of the design features that they propose. However, the lack of regulations and standards regarding building energy efficiency probably means that architects lack the incentive to offer innovative solutions to clients who are unaware of their advantages. The lack of appropriate materials in the local market may act as a further disincentive for architects to do so. Other parties identified as having a role in increasing the use of improved building design to enhance thermal comfort (not only through increasing client awareness) were the government, financial institutions/ investors, material suppliers, contractors and engineers.

The representative of the energy service provider in Male' (STELCO) also identified their main role as increasing client awareness regarding the need for and advantages of energy efficiency measures. The energy service providers were also asked about the level of detail in energy bills, as detailed information regarding consumption patterns can be important for clients in determining how best to reduce their energy consumption. However, the interviewee identified the need for costly monitoring equipment and training as barriers to obtaining detailed data regarding the electricity consumption of individual buildings (Thaufeeg, pers comm.).

5.2.4 Financial/ Economic Constraints

The lack of access to financing by the housing sector was identified as a major limitation in the housing sector of the country, especially in the rural island. This forces households to construct their residences piece-meal, room-by-room, as their economic situation permits (Aswad, pers comm.). Similarly, buildings that are originally not designed to be air-conditioned are subsequently air-conditioned, as the financial capability and expectations of the occupant changes. The use of air conditioners is thus increasing as the socioeconomic situation of the population changes. The uncoordinated and unplanned approach to construction, resulting from lack of financial capability, results in houses with suboptimal design in the long term, in terms of both their financial cost (Adam, pers comm) and their thermal performance (Baker 1987).

On the other hand, electricity accounts for 4% and 6% of total household expenditure on average, in urban Male' and rural Atolls respectively (Department of National Planning 2012). Although the cost of providing electricity from imported fossil fuels is very high, electricity bills are subsidised by the government. This means that the true cost of electricity is not apparent to clients, especially without the internalisation of externalities associated with the entire process (from fuel extraction to power generation, including environmental and health impacts). This reduces the incentive and motivation for end users to invest in energy efficient technologies.

Over half of urban households live in rented residences, while just 1% of the rural households occupy rented buildings (Department of National Planning 2012). Although similar statistics for commercial buildings are not available, it is likely that the majority of commercial buildings are also rented. This creates a situation of split incentives, where the building developer aims at minimising the upfront cost of building construction, while the occupier is interested in minimising operational costs of using the building over its lifetime. For instance, buildings intended for leasing often have low ceilings, so that the number of storeys can be maximised, given the regulatory restrictions on building height (Waheed, pers comm.). This precludes the use of ceiling fans, which are common in residential buildings and much less energy intensive, and encourages occupants to install air conditioners, according to some clients. This maximises the profit for the building owners, while increasing the cost for building occupants.

Hence, the principal-agent split also presents a significant barrier to incorporating energy efficient design features in urban buildings of the Maldives, especially since the upfront cost of energy efficient construction is usually higher than that of conventional technology. This situation looks set to be worsening in the absence of a building code that stipulates specific energy performance standards, as the percentage of rented urban buildings shows an increasing trend (Figure 10).

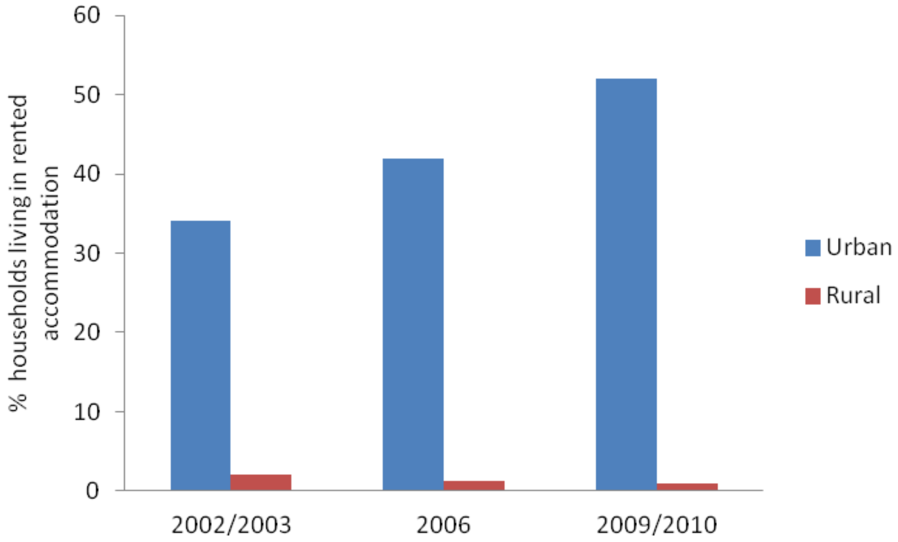


Figure 10 Percentage of households in rented accommodation in 2002/2003, 2006 and 2009/2010. (Adapted from Department of National Planning 2012 and Ministry of Planning and National Development 2008)

5.2.5 Institutional Constraints

Most of the architects surveyed agree that the level of interest shown by the government in promoting energy efficient building technology is insufficient. However, the level of interest appears to be increasing in recent times, demonstrated by the initiative to develop a 'Green Building". The Green Building Project aims to demonstrate sustainability concepts in building design and construction, and introduce new construction methods to the country (Ministry of Housing and Environment 2012).

While the interest expressed by the government in energy efficient building design may be said to be increasing, the current policies are not identified as "adequate" to facilitate widespread adoption of energy efficient technologies in the building sector. According to government officials, there are plans to develop energy performance standards in all sectors, including the buildings sector, to encourage energy efficiency. However, no such standards exist at the moment. The capacity of the government to enforce its policies and monitor compliance to regulations regarding energy performance is also questionable, especially since this requires considerable expertise and institutional support.

Government policies on financing the housing sector has been developed quite recently, as the previous government (elected in 2008) made adequate housing for all one of its key pledges. The Housing Development Finance Corporation Plc (HDFC) is the only specialised financial institution of its kind in the country. Effective since 2009, the HDFC has four different home loan schemes, available for new construction and renovation projects, in addition to a recent additional scheme designed in cooperation with the government, aimed towards facilitating the completion of buildings, the construction of which had to be stopped due to insufficient funds (Housing Development Finance Corporation PLC 2010).

However, these financing schemes are not designed to encourage energy efficient buildings per se, and do not in themselves provide an incentive or better enable clients to opt for energy efficient technology, which generally have a higher upfront cost compared to conventional technology. While there is currently an import duty exemption for renewable energy technologies, no such economic instrument is used for energy efficient technology. The Maldives Energy Authority is in the process of suggesting "amendments to the import/export act to allow for the duty exemption on energy efficient technologies, appliances, materials, etc" (Waheed 2012).

Constraints within the construction industry itself can also limit the widespread adoption of energy efficient technology in buildings, in addition to the government and financial institutions. Most architects agree that the dominant paradigm in the country with regard to the construction is one of linear and sequential processes, with little or no feedback between the design team and the construction team. While few of the architects do suggest that there is an "acceptable" level of trust between industry partners, most agree that the level of coordination between the partners is "insufficient". As the maximum energy efficiency can be achieved by considering the entire building system, the entire construction process and all its stakeholders must be involved in designing and constructing the building.

5.2.6 Reclassification of Barriers

The major physical, behavioural, informational, economic and institutional constraints to adopting building designs and technologies that will reduce the amount of energy required for thermal comfort in Maldivian buildings can be broadly classified into three categories: lack of awareness, lack of incentive and lack or resources.

Lack of awareness refers awareness regarding the importance of energy efficiency, the potential for reducing energy demand through building design and the advantages and co-benefits of reducing energy demand in buildings. Barriers pertaining to lack of awareness are also termed informational barriers, and often results in lack of trust in unfamiliar technology, by clients as well as design and construction experts. Behavioural changes that improve energy efficiency by addressing the thermal requirement of occupants are also best addressed through improved awareness and education.

Lack of incentive refers to lack of measures aimed at encouraging energy efficiency and discouraging energy inefficient behaviours and technologies. The subsidisation of electricity limits the motivation for occupants to conserve electricity. The high percentage of rented buildings, as opposed to occupant-owned buildings, results in an agent-principle split, whereby the building developer does not have the incentive to invest in energy efficiency, although the building occupant does. This principle-agent split is further exacerbated by the lack of performance standards that regulate the building industry.

Lack of resources refers to materials and technologies, financial resources, human resources and land. Scarcity of land is a physical limitation that can only be addressed by careful urban planning. However, this is a significant factor affecting the adoption of energy efficient technology in Maldivian buildings, and needs to be given high priority. The lack of materials and appropriate building technologies requires market transformation to make them locally available. Human resources include expertise in designing energy efficient buildings, as well enforcing and monitoring the policies and programs aimed at improving energy efficiency in buildings.

6 Overcoming Barriers through Market Transformation

6.1 Market Transformation Strategy

The construction industry and the market for building technologies in the country appears to be “stuck” in the existing paradigm, whereby neither the construction industry nor the clients are motivated to develop or demand energy efficient buildings. Hence, the structure of the market needs to be changed, in order to ensure the long-term sustenance of the effects of any policies aimed at increasing the adoption of energy efficient technology. “Strategic interventions that cause lasting changes in the structure or function of markets for specific energy-efficient product” are called Market Transformation Programs (Birner and Martinot 2005). This is achieved through the removal of market barriers and changing the behaviour of market actors (Neij 2001). Market transformation programmes have been carried out quite successfully for improving the adoption of energy-efficient projects, mostly in developed countries, since the early 1990’s (Birner and Martinot 2005).

6.2 Policy Measures

The Market Transformation Strategy should consist of a combination of different measures, all of which have different effects that are appropriate for different levels of market maturity (Birner and Martinot 2005; Neij 2001). The policy instruments used can be classified into three types: Legislative Controls, Economic Instruments or Support Measures. The identification of appropriate program measures and timely implementation of these measures at the appropriate stage of market maturity is a key requirement in the Market Transformation Strategy (Neij 2001). These measures need to be direct responses to identified market barriers (Birner and Martinot 2005). Table 7 summarises the key features of the policy measures deemed appropriate for increasing the adoption of energy efficient buildings in the Maldives, and their intended outcomes. The specific considerations that could determine the effectiveness of the suggested policy measures are subsequently explained further.

Table 7 Policy Measures suggested for addressing major barrier, and their intended outcomes

Policy Measure	Type of Policy Measure	Barrier Addresses	Intended effect
Public leadership programs	Support	Lack of awareness	Inform clients and construction industry of the existence and energy saving potential of energy efficient technology
Media campaigns	Support	Lack of awareness	Encourage energy efficient behaviour by occupants; Inform clients of the existence and energy saving potential of energy efficient technology; Inform clients on policy measures designed to encourage adoption of energy efficient building technology
Energy performance labelling and certification	Legislative	Lack of awareness; Lack of incentive	Inform clients of the (comparative) energy performance of buildings, thereby encouraging building developers to invest in energy efficiency and clients to invest in energy efficient buildings
Remove electricity subsidies	Economic	Misplaced incentives	Reveal hidden costs and create an incentive for energy efficient behaviour by occupants, in order to avoid financial penalties for in efficiency
Mandatory minimum energy performance standard	Legislative	Lack of incentive	Address the principal-agent split by creating an incentive (i.e. avoid legal penalties for non compliance)for building developers, who do not occupy the building and therefore do not benefit from improved energy efficiency, to introduce energy efficiency measures
Subsidised grants	Economic	Lack of financial resources	Enable clients to invest in energy efficient buildings which have higher investment costs than conventional buildings
Duty exemptions	Economic	Lack of financial resources; Lack of incentive	Enable suppliers to provide energy efficient building materials and technologies, at lower prices
Training Programs for designers	Support	Lack of expertise	Educate building designers on appropriate energy efficient building designs and technologies
Institutional capacity development	Support	Lack of expertise	Improve the design, implementation and enforcement of policy measures intended to address other barriers
Cooperative procurement	Economic	Lack of incentive; Lack of financial resources	Enable suppliers to supply energy efficient materials and technology at affordable costs; Enable clients to procure energy efficient materials and technology at lower costs
Urban planning	Support	Land scarcity	Optimise the opportunities for energy efficient design, currently restricted by urban design

6.3 Combination of Policy Measures

The energy performance labelling and certification scheme underlies the entire market transformation strategy, by providing a credible, standardised measure for evaluating the quality of buildings, and allowing prospective clients to make their decisions based on energy performance information (Klinchenberg and Sunnika 2006). It is usually used as a stand-alone informative tool designed to influence consumer choice or manufacturer's energy efficiency standards (Crossley *et al*. 2000). However, this may not produce the most effective results, especially if labelling is not made mandatory (Crossley *et al.* 2000). This is because the measure by itself addresses only part of the informational constraints, and therefore needs to be combined with other instruments that address other barriers (Klinchenberg and Sunikka 2006). Used as the basis of a complete policy package, it can be extremely effective (and cost-effective) in market transformation (Koppel and Urge-Vorsatz 2007). Trained auditors and institutional arrangements to develop, implement, monitor and evaluate the scheme are also necessary. Within this scheme, the buildings will need to be classified into performance levels. According to Klinchenberg and Sunikka (2006), buildings can be classified into three performance levels: a Minimum Performance level, a Best Practice level and a State of the Art level.

The first classification would be designed to ban buildings with the worst energy performance. Compliance with this minimum level of energy performance must be backed by legislative controls. The second classification (Best Practice) aims to commercialise energy efficient building technologies by stimulating the market through interventions designed to address barriers to both the supply and demand of energy efficient technologies. This is important since market transformation is cost-effective only if the market is large enough, and there is a learning curve, whereby the rate of adoption increases as the market actors learn from the experience of early adopters (Klinchenberg and Sunikka 2006). The learning effect benefits from improvements to the technology, which improves the performance, and/or reduces the cost of energy efficient buildings, greater acceptance and trust among market actors in the technology, and removal of market barriers and reduction in transaction costs (Neij 2001).

The demand for buildings with the second energy performance classification, whereby buildings adhere to Best Practice standards, can be increased by removing/ reducing disincentives such as electricity subsidies, and providing subsidies, subsidised loans and grants for development of buildings that qualify for this classification level, as well as conducting consumer education programmes and media campaigns to raise awareness.

Measures addressing the supply of energy efficient technology also need to be considered, since energy efficient technology can be utilised only if appropriate materials and design option are available (Klinchenberg and Sunikka 2006) in addition to skilled professionals and adequate institutional capacity. Co-operative procurement policies can be instrumental in encouraging the introduction and commercialisation of previously unavailable energy efficient building materials and technologies in the market, by increasing confidence of both suppliers and building designers (Koppel and Urge-Vorsatz 2007).

The third classification level suggested is the State of the Art, which is designed to introduce new technologies to the market. Demonstration projects are key to introducing new technologies, in order to overcome lack of awareness regarding the availability and potential of new technologies, and inspire confidence in their feasibility in everyday use (Klinchenberg and Sunikka 2006).

6.4 Considerations for Effective Design of Policy Measures

Energy Performance Labelling and Certification Scheme

Since higher levels of thermal comfort are likely to be required by occupants as they attain economic growth, and climate change is likely to produce more instances of extreme climatic conditions, the amount of energy required to provide thermal comfort may increase. On the other hand, technological improvements are expected to occur, increasing the potential for energy savings. The energy performance levels required should reflect all these factors, and should therefore be routinely upgraded to reflect existing State of the Art, Best Practice and Minimum Acceptable standards. Furthermore, the performance levels would refer not only to energy for thermal comfort, but to the energy consumption for all energy services for the building system, especially since such a systemic view would present greater opportunities for energy savings in the building system (Levine *et al*. 2007).

Mandatory Building Energy Performance Standard

In the context of the Maldives, the Compliance Documents of the National Building Code can stipulate minimum energy performance levels for different building types, which evolve as attainable energy performance levels change over time. Although measures-based building codes that stipulate specific design features to be adopted are more easily enforced, a performance based building code may be more appropriate in a market transformation framework, especially since it would drive innovation, facilitating sustained improvement in energy performance beyond minimum legislative requirements (Koppel and Urge-Vorsatz 2007). However, a performance-based building code would require more sophisticated institutional arrangements, especially for implementation and enforcement, which is often lacking in developing countries (Koppel and Urge-Vorsatz 2007).

Since awareness and expertise in energy efficient buildings is low among professionals such as building designers, architects, etc., many developing countries introduce the standards on a voluntary basis to raise awareness, before making them mandatory. In the voluntary stage, standards can be combined with incentives such as subsidised housing loans or penalties such as allowing tenants to pay less rent if the standards are not met by the owners, in order to increase compliance (Koppel and Urge-Vorsatz 2007). Demonstration projects led by the public sector, and education programmes aimed at building designers can be instrumental in educating building designers with regard to specific design options available to reach the required performance standards.

Economic Incentives

Peculiarities of the building sector result in market failures that discourage the adoption of energy efficient building designs. Such peculiarities include the fact that the benefits of energy efficiency mostly accrued to the society, while cost is usually wholly borne by the building developer. On the other hand, the initial cost of energy efficient buildings is very high, while the benefits are realised over the long term (Klinchenberg and Sunikka 2006). The subsidisation of electricity bills, which prevent end-users from realising the full cost of energy use also presents a significant disincentive to energy efficiency in general (Levine *et al*. 2007). Furthermore, residential buildings have a societal dimension, since housing is a social right. Therefore, policies regarding housing are largely influenced by political factors and regulators are often unwilling to enforce mandatory building energy performance standards for residential buildings in particular (Klinchenberg and Sunikka 2006; Crossley *et al*. 2000).

Hence, such disincentives need to be removed, in order for the market transformation policies to be effective. The subsidies on the cost of electricity should be reduced in phases, since abrupt changes can have economic and political repercussions. For instance, complete and abrupt removal of subsidies could lead to non-payment of electricity bills (Levine *et al.* 2007). Disincentives arising from the high initial cost of energy efficient buildings can be addressed through introduction of incentives to encourage and facilitate the adoption of energy efficient technologies.

The success of other policies designed to increase the adoption of energy efficient buildings will depend very much on the amount of funding available (Crossley *et al.* 2000), especially given the high initial cost of energy efficient building technologies compared to conventional technology, identified as a major barrier in the country. Funding mechanisms include economic instruments such as public benefits charge, tax exemptions and incentives, subsidies and loans, and energy or CO_2 taxes (Crossley *et al.* 2000).

Although taxes can be a potential revenue stream for public investments in energy efficiency, they fail to address the barriers to energy efficiency, in addition to having negative social and political impacts. On the other hand, tax exemptions and reductions, subsidies, grants, loans and rebates facilitate investment in new (more expensive) technology, and make them affordable to even poor households (Crossley *et al.* 2000). Tax exemptions are currently in place for renewable energy technologies in the country (Waheed, pers comm.). This policy should be extended to include energy efficient appliances and building technologies as well, to stimulate the market by increasing the availability of and demand for such technology. Since air-conditioner use is increasing rapidly in the country, and the trend is expected to increase in the future, special attention should be given to incentivising the import and purchase of more energy efficient air conditioning systems in particular.

Subsidies, grants and other financial assistance are effective in developing countries, as they make energy efficient technology more affordable to a greater proportion of the population (Crossley *et al.* 2000). Subsidised loans can be provided within the framework of the HDFC housing loan schemes, to applicants proposing to construct buildings designed to achieve Best Practice levels in energy performance. Since the energy performance required to qualify for Best Practice certification changes over time, this measure is likely to remain effective even though such measures usually work best when introduced for a limited time period (Crossley *et al.* 2000). However, the effectiveness of this measure also depends on the extent to which potential clients are aware of the incentive and the co-benefits, and ensuring that the amount of subsidy is sufficient to incentivise the additional cost for energy efficient measures. Since the demand for housing in the country is likely to keep increasing as the population becomes increasingly urbanised and the economy grows, combining incentives for energy efficiency measures with measures related to the housing sector could be beneficial.

Co-operative Procurement

Co-operative procurement can be a very effective tool for market transformation, since it is based on a coordinated effort to directly influence the market by creating demand for a specific product (Koppel and Urge-Vorsatz 2007). Customers collectively define their requirements, invite proposals, choose suppliers and buy the products. In the Maldivian context, Maldives Association for Construction Industry (MACI) appears to be an ideal institution with the incentive and technical expertise required to identify appropriate products, materials and technologies and evaluate the proposals from suppliers. This type of cooperative action will increase the confidence of individual clients in the feasibility of new (unfamiliar) technology. In order to be successful, a long-term relationship between the buyers and suppliers must be established, which will be facilitated by the availability of the financial resources needed for such an initiative. Financial incentives by the government, for instance in the form of tax exemptions, may be important in this respect.

Training and Capacity Building

This is one of the most critical measures needed for the successful development and implementation of all of the other policy measures. The energy performance labelling scheme requires in-depth research to determine the level of energy performance that can be achieved as well as the cost associated with improved energy efficiency, in order to specify the three energy performance levels. Furthermore, trained auditors will be needed to evaluate the energy performance of each building, which in itself is a costly and difficult process. The certification scheme must be administered by an independent body, the credibility and activities of which will need to be monitored and verified by the relevant government authority. The implementation and enforcement of the economic measures will also require dedicated institutional resources and skilled personnel. Furthermore, the construction industry, and especially building designers, will need to be educated with regard to energy efficient building design and techniques, in order to enable them to design buildings that meet requirements.

Public Leadership Programs

Public leadership programs which demonstrate the use of State of the Art energy efficient buildings can be extremely effective in market transformation for two reasons- the public sector accounts for a large share of the total energy consumption, and successful public leadership programs can inspire private sector confidence in new and unfamiliar technology and building design features (Crossley *et al.* 2000; Neij 2001). The Green Building project initiated by the Maldivian government is an example of such a program. However, in order to be effective in market transformation, the scale of the project should be large enough, and the details of the design and results of the project should be made public. The involvement of private sector experts in the project (Ministry of Housing and Environment 2012) is a favourable factor, since it will serve to increase the capacity and experience of private sector actors in the construction industry, in aspects of energy efficient building design and construction. Public sector leadership programs require political commitment in order to be successful (Crossley *et al.* 2000), which might be difficult to achieve in the absence of a coordinated national policy towards public leadership programs, since different areas of the public sector have different priorities, which may conflict with energy efficiency requirements. Hence, public leadership programs are also most effective when made mandatory (Crossley *et al.* 2000).

Linkage with Other Sectoral Policies and Projects

Energy performance of buildings is very much dependent on the characteristics of the urban environment within which it exists. This is especially true with regard to energy use for thermal comfort, since the thermal environment of the building is determined largely by the microclimate created by the urban environment. Therefore, urban design features, such as the clustering of buildings, orientation of building plots, mixing of different building types and the existence of green spaces, affect the opportunities for reducing energy used for providing thermal comfort in buildings (Levine *et al.* 2007; United Nations Environtment Programme 2007).

Urban design is particularly important in the Maldives, given the situation of extreme land scarcity. Optimising the opportunities for energy efficiency through building design therefore requires optimising the urban land use plan, to make the best use of available land. The urban design also affects the opportunities for linking the cooling requirements of several buildings into an integrated system that is provided for by a district cooling system, which might be more efficient and cost-effective than individual cooling systems in every building (Levine *et al.* 2007). Hence, urban planning and land use policies should ideally be designed with careful consideration of implications for energy demand.

Regulation of the energy performance of buildings is often complicated due to the fact that housing is a social right, and alleviating housing shortages in the short term usually takes priority over improving energy performance of buildings, usually at higher cost. It is in the long-term interest of the society and individuals who own and occupy buildings, to invest in energy efficiency. However, this long-term benefit needs to be made more apparent and taken into account when designing housing projects. Since the country is currently in the midst of a construction boom, due to the government's pledge to provide adequate housing, opportunities for integrating the government's commitment to achieving carbon neutrality with the housing development projects should be fully exploited, in order to achieve cost-effective solutions in the long-term.

The large number of social housing projects currently under way or planned to be conducted in the near future provides huge opportunities for energy performance contracting (whereby housing projects are awarded to parties with the best proposals in terms of building energy performance). Integrating the housing sector plans with the renewable energy programs planned to be conducted, through the use of Building-integrated photovoltaic panels (BiPV) may also be a beneficial opportunity for optimising the opportunities for achieving carbon neutrality by 2020. BiPV can be used to a significant portion of the remaining energy demand, after exploiting the opportunities for reducing energy demand through passive strategies such as optimising the building design and changing occupant behaviour (Levine *et al.* 2007; Bernard *et al.* 2010).

7 Conclusions

The thermal environment existing in the buildings studied do not meet the thermal requirements of the building occupants, except for the urban office building. While buildings with unacceptable thermal comfort levels may be tolerated now, current trends in air-conditioner ownership suggest that this will mostly result in increased ownership of air-conditioners, in both urban and rural buildings, as expectations of the occupants, and their financial capability increase.

The survey of existing building design characteristics and occupant characteristics suggest there is significant scope for building design and occupant behaviour to be improved, so as to reduce energy demand for cooling using passive strategies. However, several factors prevent such improvements in building design and occupant behaviour. These factors can broadly be classified into three types of barriers: lack of awareness, lack of incentive and lack of resources. All of these contribute to the stagnation of the market for energy efficient homes. Lack of awareness, incentive and financial resources inhibit demand for energy efficient homes, while lack of human resources (skilled professionals and regulatory agents) and the small size of housing plots are major barriers to constructing energy efficiency buildings, assuming they were in demand. Therefore, there is very limited market for energy efficient buildings in the country.

This situation requires a strategy that addresses both the demand and supply of energy efficient buildings, leading to a sustained change in market structure. A Market Transformation Strategy is therefore recommended, consisting of a mix of measures having different intended outcomes, which would address the identified barriers. The major requirement for the market transformation strategy is an energy performance labelling and certification scheme, which evolves in response to changes in technology, and is backed by legislative, economic and informational measures to maximise effectiveness. Energy efficiency policies must also be integrated with existing policies in related sectors, such as housing and adoption of renewable energy technologies.

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