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The adoption of PV systems in the Maldives: A technological review

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ABSTRACT *This review begins with a brief outline of PV usage in the Maldives followed by a discussion of PV systems in general with a special emphasis on grid-tied systems. Irradiation levels in the Maldives are then outlined. A short review of the components of grid-tied PV systems and their technical requirements are then presented. The review concludes briefly noting the findings of studies carried out to evaluate reliability, modes of failure, trends and recommendations for research in grid-tied PV systems.*

Keywords: PV systems, PV adoption, solar energy, Maldives, renewable energy, grid-tie inverters, microinverters, trends in PV system, PV research focus, comparison of inverters

Introduction

The Maldives faces a serious energy crisis. According to Japanese International Cooperation Agency [JICA] (2009) the total energy consumption has been increasing at more than 10% per year. Already, petroleum imports accounted for 31% of GDP in 2013. In fact, petroleum products constitute the largest category of imports. Compared to 2011, the expenditure on fuel rose by 33% in 2012. Electricity generation consumed the largest share of the imported fuel (Ministry of Economic Development, 2013). Dependence on imported fuel is a serious impediment to national development. The population increase envisaged in the future is likely to exacerbate the crisis.

One of the most viable ways of mitigating the energy crisis would be to invest in renewable energy. Of different forms of renewable energy available to the Maldives, namely, geothermal, wind, ocean current and solar, photovoltaic (PV) solar power systems appear to be most promising. The Maldives does not have regular strong winds nor rivers for hydroelectric power generation—two of the most common renewable energy resources in most countries where these forms of energy are viable due to their geography. However, the Maldives receives a solar irradiation intensity of average 5.2 kWh/m2/day for most days of the year. The average sunshine hours are 2784.5 per year (JICA, 2009). This level of irradiation is promising for most solar energy applications. PV solar power has the following advantages: the technology is mature, cost almost at par with diesel engine generated electricity, scalable, the systems are modular, and energy availability is not location-specific.

However, despite the abundance of sunshine, the take-up of PV systems has been rather sluggish. Of the 250 MW installed capacity of electricity generation, just over 2 MW or 0.8% constitutes PV systems (Ministry of Economic Development, 2013). This percentage had risen to 1% as of December 2014 (Ministry of Environment and Energy, 2014a). In terms of

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national development greater utilization of solar energy, more particularly PV systems is a necessity. In fact, the Government wishes to ensure that 50% of power generation by 2025 is by renewable energy (Ministry of Economic Development, 2013). A number of initiatives to encourage businesses and the public to invest in PV systems has been proposed, but, at present, they are not well implemented.

Statement of the Problem

Both JICA (2009) and the Ministry of Economic Development (2013) notes that the electrical energy usage has been rising at a value greater than 10% annually. This level of growth will impact the recurrent costs of public institutions harshly especially at a time of national austerity. Figure 1 shows the utility charges for the atoll campuses of the Maldives National University (MNU), 2004–2013. MNU forms an illustrative case for many State-owned enterprises. Because of the way accounting is carried for annual reports, the utility charge group includes postage though postage represents only a small, almost a negligible amount of the total expenditure. Water charges are excluded as municipal water connections were unavailable until the end of 2013. Therefore, the graph in Figure 1 represents mainly electricity costs. The numbers are shown in MVR (1 MVR is approximately US 0.07).

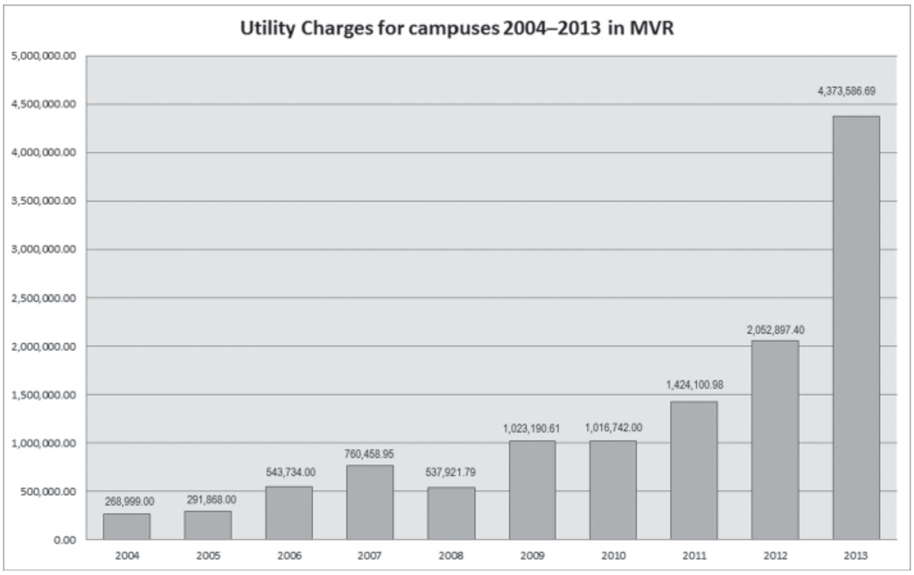

Figure 1. The expenditure on utility charges (mainly electricity costs) of the Maldives National University has been rising in the past four years.

From Figure 1, one observes that for the past five years, except for a slight dip in 2010, the trend is a rise in the expenditure on electricity. From 2012 to 2013, the expenditure has more than doubled. This increase is attributed to increased consumption of electricity arising from the establishment of the Gan Campus in Hadhdhumathi Atoll and other causes. Many teaching spaces previously not air-conditioned have been air-conditioned. Air-conditioning costs constitute the major part of the operational costs of a campus. The atoll campus operations have also become more extensive with night classes becoming regular activities. Electricity costs have also increased in the past few years.

Utility charges constitute the third highest expenditure of MNU after staff costs and expenditure on teaching resources. In 2013, it constituted 12% of the total expenditure. Air-conditioned working spaces are becoming the norm in public institutions; therefore, it is likely that the electricity costs would increase in the future. The increase would arise from increased tariffs due to global petroleum price increases and from air-conditioning more working spaces. Additionally, such spaces are used more regularly. This illustrative case is representative of many State institutions in terms of electricity usage.

Review Objectives and Significance

There are four objectives of this review. Briefly, they are as follows:

1. To document the adoption of PV systems in the Maldives from a historical perspective.
2. To organize the literature related to PV systems development as relevant to the Maldives.
3. To synthesize literature related to PV system technology, architecture and performance.
4. To identify research gaps and recommend new research areas with particular reference to the Maldives.

This narrative review is aimed at students, novice researchers and decision makers and brings together the status of PV adoption in the Maldives from the very beginning till the end of 2014. The review is a mix of historical and status-quo review as defined by Noguchi (2006). That is, the review traces the development of PV power systems in the Maldives from the beginning together with the current state of grid-tied medium power systems and associated technological considerations.

The significance of the review may be gleaned from the introduction. An important goal of the Maldives economic diversification strategy is to ensure that 50% of the total installed capacity for power generation is derived from renewable sources by 2025 (Ministry of Economic Development, 2013). At present (2014), the percentage is 0.8 and with almost 10 years left to reach the goal, Maldives must accelerate its investment in renewable energy, most notably PV systems.

Photovoltaic Solar Power Systems in the Maldives—a brief history

Solar photovoltaic (PV) power had been used in the Maldives since the mid-70s of the twentieth century. The first use of PV power was to charge batteries for island to island communication. At that time, walkie-talkies and Citizen Band communication sets were used among the islands for official telephony. According to Abdulla Waheed (personal communication, June 20, 2014), a medical doctor who worked in Kulhudhuffushi island in Haa Dhaalu Atoll, photovoltaic power was used to run vaccine coolers in the early 1980s in

Kulhudhuffushi. When he started work in Kulhudhuffushi hospital in 1984, however, the system which was installed by UNICEF had ceased to function due to battery failure. In 1987 in Ugoofaaru Hospital (established in 1986 through an IHAP by USAID), a PV system was installed in the hospital which powered the fans, lights and other small loads (Hameed, Nott, & Reid, 1985).

A similar PV system set up by UNICEF was in operation in the 18-bed Addu Regional Hospital. This system in Addu Atoll Hospital was donated to the Maldives College of Higher Education in 2000 as it became unnecessary when reliable public electric power became available. The Maldives College of Higher Education, the precursor to the Maldives National University, maintained a campus in Addu Atoll. The PV system donated by the Addu Regional Hospital was installed on the roof of the campus for demonstration. It was a polycrystalline PV system of 4 kW. When the Campus took ownership of the system, neither the inverter (the electronics for converting DC into AC) nor the batteries were in working order. That system, repaired with new inverters and batteries, was used to power a fountain pump. It is operational as of today.

Dhiraagu, a telecom company partly owned by the government is an early adopter of solar energy. In the 1990s, the author witnessed one of their PV systems to power microwave links used in Laamu Atoll. According to Dhiraagu (2012), there were 174 islands where PV systems were operating with a total area of 1,901 square metres producing 228,476 KWh of renewable energy per year. In terms of distribution this is by far the most extensive utilization of PV power from the beginning—a use for which PV power is most appropriate. However, these systems are small as the power requirements for microwave relay stations are not a heavy as for domestic or civil use. Throughout the 1980s and 1990s, small PV systems were in common use in harbours, and on fishing vessels for charging navigation light batteries and other shipboard uses.

The first PV-Diesel hybrid system was installed in Mandhoo Island in 2005 as a collaboration pilot project by "Strengthening Maldivian Initiatives for a Long-term Energy Strategy (SMILES) and Renewable Energy Technology and Development and Application Project (RETDAP). These projects were funded by the French Agency for Environment and Energy Management (ADEME) and the Utrecht Energy Research of the Netherlands and Global Environment Facility and the United Nations Development Program respectively (JICA, 2009). The PV system in Mandhoo island, located 100 km south west of the capital, Male'. The island has a population of 373 persons at that time. The system comprises 160 panels of 80 Watts made by BP Solar giving a total of about 12.5 kW. The system was modeled on HOMER, a popular microgrid modeling software from Homer Energy. The design and performance of the system have been widely reported in the literature (Van Alphen, Van Sark, & Hekkert, 2006; Van Sark, et al., 2007).

From 2000 onwards, the economies of PV systems were well realized and adoption rate increased dramatically. Following the 2004 Tsunami, the Japanese Government installed two PV power systems in Laamu atoll. One was in the Multipurpose Building in Gan and the other was in the island office in Fonadhoo (JICA, 2009). The Laamu atoll systems are connected to the 400 V (3-phase) / 230 V (single-phase) distribution line; and power supply for emergency loads can be continued in the event of the failure of the main distribution line.

In January 2008, reportedly the world's first Hybrid AC Coupled Renewable Energy Micro Grid was installed in North Thiladhunmathi Atoll Uligamu. It was a joint venture among the State Trading Organization, Maldive Gas and USAID. In this system, 2.4 kW of PV power were integrated into the wind turbine and diesel electric power systems. The details of the system are in the Proceedings of the AUPEC Conference, Perth, December 2007. This system was also modeled on HOMER.

The first large scale single PV system installed in the Maldives was the 70 kW system on the resort island known as Sonevafushi in 2009 (Sloan, Legrand, & Chen, 2009). From this experience, more and more resorts in the Maldives began to invest in PV systems.

With the change of government in 2008, renewable energy became an area of government focus. The government approached the Japanese Government for a technical/financial feasibility study to introduce grid-tied PV power in Male' and Hulhumale' islands. Following the feasibility study, the Japanese government, through JICA, implemented the first phase of the follow-on project of the study. The installed capacity of 395kWp of PV grid-connected power was derived from systems on the rooftops of five public buildings namely the President's Office, Maldives Center for Social Education, Hiriyaa School, Thaajudhdheen School and State Electric Company (STELCO) Building. The second phase included the installation of 280kWp of Solar PV grid connected systems on the roofs of Velaanaage Building, Ghiyaasudhdheen School, Kalaafaanu School, Central Administrative Building of the Maldives National University and Faculty of Health Sciences. Both phases contributed a total of 675 kWp to Male' grid. Panels were installed on the roofs of Ministry of Finance and Treasury and Hulhumale' Hospital in the third phase of the project. At the conclusion of the project, there were 740 kW installed capacity (Sun, 2014, May 14).

An important primary study on PV systems for Thinadhoo was prepared by Amara and Bloembergen (2011) for the Ministry of Housing and Environment. It was in preparation for renewable energy and energy efficiency investment plan and bidding for Thinadhoo Island. The report is noteworthy in that it is developed for a southern atoll and contains most of the considerations for installing a PV system in a medium sized island environment. The authors belong to KEMA — a well-known energy consultancy company of Netherlands. Following the study, on 25th January 2014, 300 kWp of solar PV systems, installed on three buildings of Thinadhoo by a Chinese company (CECEP Oasis New Energy Technology), became operational (Ministry of Environment and Energy, 2014b). The system was to undergo another development. In December 2014, a HyGrid fuel reduction system was installed connecting all PV systems. This system from the German company, DHybrid Power Systems was used for networking all control units, transformer control systems and other equipment, over a distance of 4 km using DSL lines (DHybrid, 2014).

On January 9, 2012, a 61 kW PV system on Muhyiddin School in Viligili was switched on. It was to be the first of 652 kW of PV power to be installed across six islands through a power-sharing agreement signed between STELCO and

Renewable Energy Maldives (REM) (Robinson, 2012). REM also installed a sizeable PV system on another school in Male' — Billabong which became operational on 6th May 2013. (http://www.haveeru.com.mv/video/735). REM together with WIRSOL APAC GmbH has installed altogether 652 kW in six islands in the Maldives (Ministry of Environment and Energy, 2012).

The government signed an agreement with Japanese representatives on 17th March 2014 to establish a 40 kW PV power systems in Dhiffushi island in Male' Atoll (Ministry of Environment and Energy, 2014c).

In January 2013, the first phase of a study by AF-Mercado EMI on Solar PV Integration in the Maldives commissioned for the Asian Development Bank and the Maldives Energy Authority was released. They grouped the consumers into four categories: very small or small islands (<100 kW), medium and large islands (several hundred kW including MW-scale peak), resort islands in the range of 300-800 kW peak load and Male' region. On the basis of case studies, they concluded that about 30 to 50% penetration by PV power systems is possible for medium and large islands, whereas for Male' region the corresponding figure is about 25%. Diesel cost savings would be 22–36% and 16% respectively for medium islands and Male' region (AF-Mercados EMI, 2013). The study was undertaken by Clean Energy Climate Mitigation Project funded by the World Bank.

On October 22, 2014, 203 kWp PV power was connected to the grid on the island of Kudahuvadhoo (Minivannews, 2014). A similar project of lower capacity, 124 kWp was connected to the grid of Ugoofaaru island on November 17, 2014 (Sun, 2014, November 17). These two projected were implemented through the assistance of the German government.

As of October 2014, the installed generation capacity of electricity from all sources is 268.8 MW. Of this total, 39% of the power is generated in tourist resorts, 53% is power produced in inhabited islands, 7% is produced in industry. One percent or 2.8 MW is from PV power as of October (Ministry of Environment and Energy, 2014a). This source, Ministry of Environment and Energy (2014a), also lists the islands where most of these PV systems are located and their peak power. On November 26, 2014, a resort island called Gasfinolhu, in a first for the Maldives, switched on 1.6 MW of power to fully power the operations of the resort and bringing the total installed PV power to 1.6% (Anees, 2014).

These developments reflect the fluid nature of the adoption of PV in the Maldives. With three drivers, private participation, Government initiatives and economic imperatives, the next decade will see accelerated adoption of PV power in the Maldives. The energy requirements of a few islands are, at present, completely met by PV systems alone during day time. The following sections discuss the PV power systems in general, with particular reference to PV grid-tied systems. However, the next section is about solar irradiation—the actual source of PV power.

Solar irradiation in the Maldives

Long before the flurry of PV installations in the recent past, the potential of PV for the Maldives had been realized and many had advocated their adoption and modes of government encouragement since early 1980s (Hameed, 2004). This realization is based on the location of Maldives, the sunny climate, technological developments and the lack of other alternatives sources. Mohamed (2012) used simulation software to build a case for utilizing PV power for part of the electricity loads in small communities where diesel electric generators are exclusively used. He noted that this is economically viable and leads to uninterrupted supply for essential electrical loads in periods of outages.

The energy available for PV power systems comes directly from the Sun. The solar irradiance is defined as the amount of radiant energy incident on one square metre of Earth's surface. The National Renewable Energy Laboratories of the US has computed solar irradiation for Maldives using satellite data (Renner, George, Marion, Heimiller, & Gueymard, 2003). Their conclusion suggests that the Maldives has sufficient solar resources for PV:

> The study shows that ample resources exist throughout the year for virtually all locations in Sri Lanka and the Maldives for PV applications, such as solar home systems and remote power applications. In the Maldives in particular, the high levels of solar resource throughout the entire country make it well suited for off-grid, island-based photovoltaic applications as an alternate to, or supplement to, diesel power generators. Because of the general high level of cloudiness and humidity associated with tropical settings such as this, the resources for concentrating solar power are generally less than adequate, except for certain times of the year. (p.16)

However, the values of irradiance found by Renner et al. (2003) were noted to be about 15% higher than what was measured at Hulhule between 2003 and 2005. Hulhule is the island where the main international airport is located. The ground level measurements gave an average of 5.03 kWh/m2/day according to Van Sark et al. (2006). The most recent data available are from JICA (2009) and may be taken as the most reliable data of daily insolation for Male'. The data they used for their study are given in Table 1. The irradiation level is more than adequate for extensive adoption in the Maldives.

Table 1
Horizontal Plane Solar Irradiation for Male' in kWh/m^2/day

Month	Irradiance	Month	Irradiance
January	5.23	July	4.51
February	5.61	August	5.60
March	5.99	September	4.56
April	5.24	October	6.06
May	4.86	November	4.00
June	5.06	December	5.10

Average: 5.15 Source: JICA, 2009, p. A-6-10

Amara et al. (2011) gives horizontal irradiation data for the island of Thinadhoo in their report (page 27). However, the data were obtained from Retscreen® International Clean Energy Project Analysis Software and not measured on ground. Their average irradiation (horizontal component) for the island is 5.87 kWh/m^2/day which appears to be higher than the measured value at Hulhule or Male'.

The next section outlines the technologies common in PV systems.

PV Power Systems

There are usually two types of PV systems: grid-tied and off-grid systems. Off-grid systems are independent of the utility power grid. Typically, off-grid or stand-alone systems have a number of PV panels producing DC. The DC may be used to charge batteries or may directly power other appliances. Often, for household appliances, an inverter is used to convert the DC into AC at the appliance voltage. When the panels are not producing power (typically at night) the inverter may be run from the batteries. There is no inter-connection between the PV system and the grid—the network of electrical transmission lines connecting generating stations to consumers in a given area. The absence of interconnection is the distinguishing feature between an off-grid PV system and grid-tied system (Al-Adwan, 2013). In contrast, a grid-tied or grid-connected PV system usually has no batteries and the PV system is connected to the grid through an inverter. Grid interconnection has the advantage of better utilization of generated power. Batteries which are a major cost of an off-grid system, is not essential. When sun is available, excess power generated is fed into the grid at an agreed tariff. At night or when PV power is not available the owner of the system consumes power from the grid. Figure 2 shows a general block diagram of a grid-tied PV power system.

Grid interconnection requires the grid owner, to agree to quality of power generated. Safety issues are involved as well. The technical requirements for grid connection are determined by the relevant authority in each country. In the Maldives it is the Maldives Energy Authority (MEA). Their specifications are in the published document, entitled "Guidelines on Technical Requirements for Photovoltaic Grid – connection." This document specifies issues regarding frequency limits, voltage fluctuations, islanding detection, and other attributes of the system (Maldives Energy Authority, 2013).

Kaundinya, Balachandra and Ravindranath (2009) reviewed 102 studies of grid-tied versus stand-alone electric energy systems. They found that most studies are context dependent and context specific precluding the findings of the economic-financial assessment objective. However, Eltawil and Zhao (2010) reviewed literature on technical and potential problems of grid-tied PV power systems and noted that grid connected PV power systems have become the dominant technology for PV electricity accounting for over 75% of all installed PV power systems by 2005. In the Maldives, grid-tied systems dominate the market accounting for almost all installed capacity.

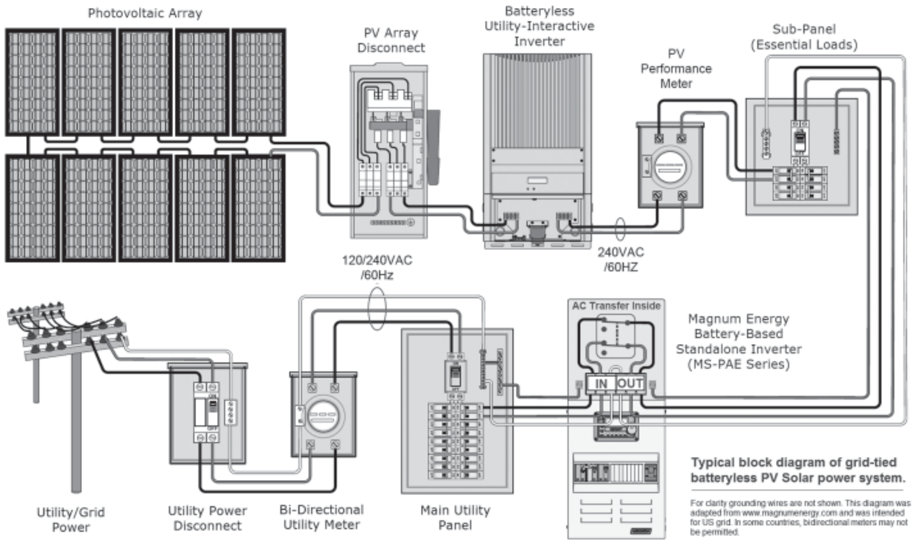

Figure 2. Typical block diagram of grid-tied batteryless PV system.

Grid-tied PV power system components

PV Panels

Scarcity of land dictates that any PV system in the Maldives must maximize available space. Since PV solar array takes most of the horizontal area, this is where considerations of space must be focused on. In this regard, from the point of view of area conservation, panels using highly efficient PV cells are desirable. There are many types of PV solar cells available, but the most common are made of silicon. The three main types of silicon cells are monocrystalline, polycrystalline and amorphous. The efficiencies obtained in laboratory settings are reported every six months in the journal Progress in Photovoltaics. Al-Adwan (2013) outlines how efficiencies of commercial cells are evaluated. The efficiencies of commercial PV cells are summarized by JICA (2009) as is shown in Table 2. The price appears to be installed price per watt.

Table 2
Comparison of Silicon Solar Cells

Attribute	Monocrystalline	Polycrystalline	Amorphous
Size	10–12.5 cm	15.5 cm	140 cm x 110 cm
Efficiency	15–20%	12–17%	8–12%
Price	US$5–6/Watt	US$4/Watt	US$4–5/Watt

Source: JICA, 2009

JICA (2009) recommends monocrystalline silicon type for the Maldives because the required space for the same output is smaller. Japanese installations in the Maldives feature all monocrystalline cells.

An important feature PV panels is that the panel voltage decreases as the current drawn from it increases. The literature provided by the manufacturer of the panel often includes the current and voltage curve of the panel. Figure 3 shows such a curve. When the current is zero, the open circuit voltage is 37 V. As more current is drawn, the voltage tends to drop until it becomes zero at short-circuit. The short-circuit voltage is 8.34 A. As power is current multiplied by voltage, there is an optimum voltage at which the panel produces maximum power. This point is known as maximum power point and is labelled in Figure 3. In typical systems, it is the task of a DC to DC converter to operate the PV array at the optimum voltage for maximum power. This function is called Maximum Power Point Tracking (MPPT) and the necessary DC to DC converter is often incorporated in the inverter box. There are single-chip controllers for MPPT. For example, Texas Instruments SM72442 is a programmable single chip MPPT controller providing driving signals for a 4-switch buck-boost converter.

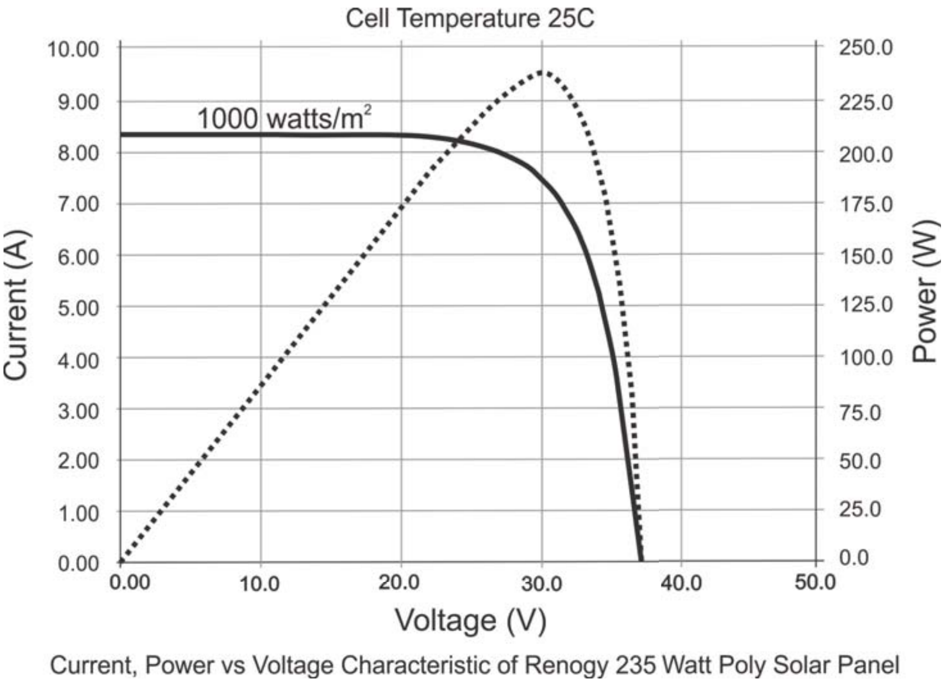

Figure 3. Characteristic Voltage Curve for a commercial panel (Renogy 235 Watt).

Grid-tie inverters and microinverters

Most household appliances and other loads operate on 230 V alternating current (AC), and PV solar panels produce direct current (DC). Therefore, to utilize solar energy effectively, a power inverter is required. An inverter changes

DC into AC. The alternating current has to be produced at the voltage and at grid frequency. In the Maldives, for general household use, electric power is supplied at 230V AC and 50 Hz. With regard to the waveform of AC produced by the inverter, there are essentially two types of inverters: square wave inverters and sine wave inverters. Square wave inverters are usually not suitable for many household appliances. As grid current is a sinusoidal, sine wave inverters are required for grid connection. Sine waves are generated by using Pulse Width Modulation (PWM) techniques using semiconductor "switches." The semiconductor switches, usually MOSFETs or IGBTs, generate high-frequency high-voltage rectangular pulses, which are, next applied to a low-pass LC filter. The LC filter produces the moving average of these rectangular pulses. The required 50 Hz (or 60 Hz as the case is for US) sine wave is produced by suitably modulating the duty cycle and periodically changing the polarity of the pulses. Microcontrollers for processing the necessary signals are available as a single piece. The energy fed into the grid has to be in phase (synchronous) with grid power. If the power of the PV system is high, three phase inverters are normally used.

The efficiency of the inverter is a major feature of the efficiency of the whole PV power system and much research has taken place about the design of inverters. There are many designs of inverters principally aimed at increasing efficiency and reliability. For example, Mekhilef, Ahmed, and Younis (2008) described a general design for a 3 kW three phase grid-tie inverter. A diagram of their inverter, typical of grid-tie inverters, is depicted in Figure 4. The design of Mekhilef et al. (2008) uses an analog to digital converter (ADC) to track maximum power point. The digital values are used by the microcomputer to generate the modulation index which is used as input to pulse width modulation (PMW) generator to get the required sine waveform.

Transformers were used to isolate the PV power system from the grid. Transformers ensure that dangerous DC faults are not transmitted to the grid. DC in the grid may saturate distribution transformers and render traditional house meters unusable.

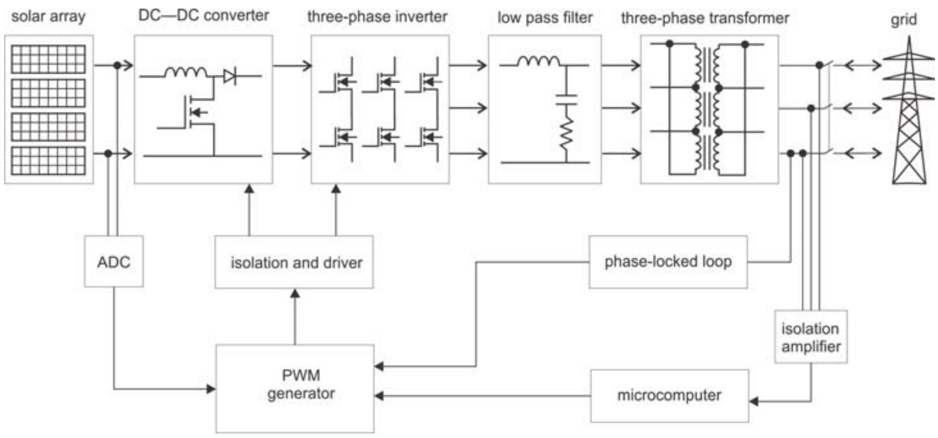

Figure 4. A system level diagram of a grid-tie inverter with associated cabling. In many inverters, the microcomputer's role is taken over by microcontrollers. The transformer is useful in isolation but wastes energy.

However, in US in 2005, and in many other countries the requirement to galvanically isolate the PV system has been removed. To ensure safety, ground current detection and other methods are used to identify possible fault conditions. Transformerless grid-tie inverters have the advantages of higher efficiency, (typically 1 to 2% higher than equivalent systems with transformers), less cost, less volume, less weight and less complexity (Gu, Dominic, Lai, Chen, LaBelle, & Chen; 2013). A typical transformerless configuration is shown in Figure 5. The dotted line shows the digital signal processing part, the heart of which is a microcontroller. Gu et al (2013) have demonstrated inverters with efficiencies greater than 99% using superjunction MOSFETS, zero voltage crossing and zero current crossing switching.

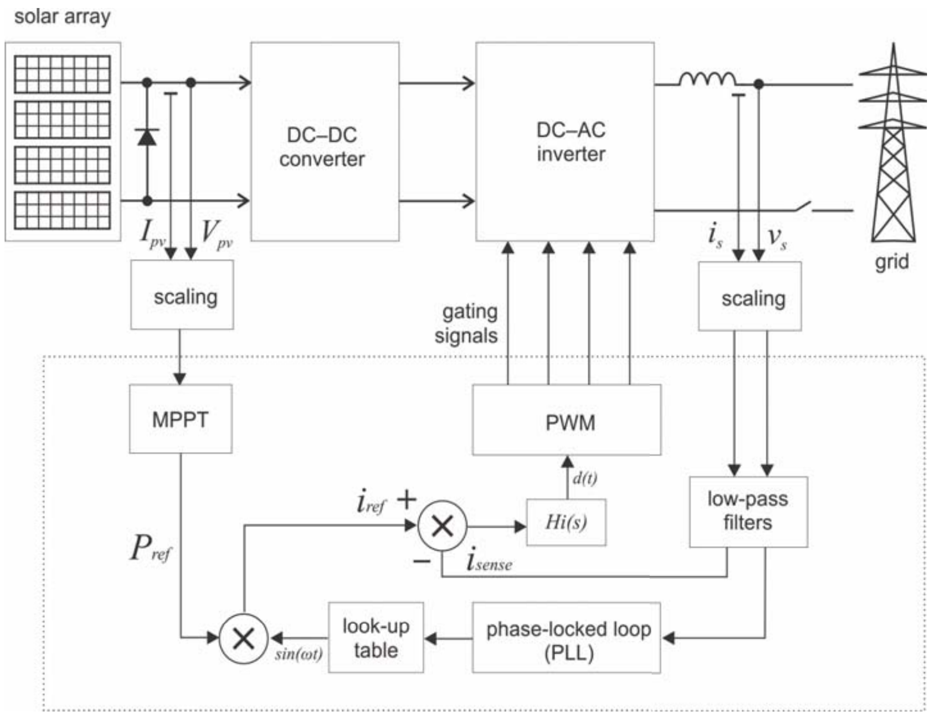

Figure 5. A transformerless grid-tied PV system After Gu et al (2013).

A new trend in grid-tie inverters is the use of microinverters instead of one large central or string inverters. A PV system using microinverters is shown in Figure 6. In a grid-tied microinverter configuration, each PV panel has a small inverter which changes the DC produced by the panel into grid-compatible AC. The outputs of all the microinverters are connected to the grid. The microinverter does all the processing that a large central or string inverter does, including MPPT and ensuring that the output is compatible with grid requirements. The claimed advantages of microinverters include redundancy; if the string or central inverter breaks down, the whole system breaks down. But with microinverters, a non-functional panel or microinverter will only lead to the loss of power produced by that panel. This advantage is particularly apparent when shade or dirt on one panel reduces the output of that string of panels. Another advantage is that each panel can be oriented to give it the best sun—a feature difficult to implement in an array. Yet, another advantage of microinverters is that MPPT has to be done for one panel, not for the whole PV array. MPPT performed at each panel by a microinverter will yield better overall system results than MPPT done for the whole PV array. Replacing a faulty panel or microinverter is straightforward, whereas for a central large one, the costs and the difficulties would be more. The system is also expandable as one has to add new panels and microinverters to increase yield. Other advantages include that the main connections are at grid voltage not at 300–600 V DC as the case is with central inverter systems. The grid voltage is safer and the normal residual current circuit breakers will protect the system and the workers in the event of a ground fault. Microinverters are now available with over 25 years of warranty indicative of its reliability and hence less downtime.

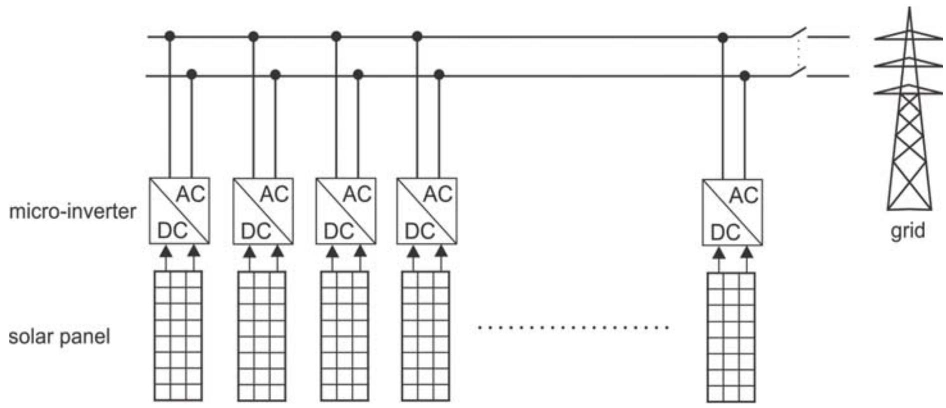

Figure 6. A grid-tied PV system based on microinverters has a higher redundancy than systems based on string inverters.

The advantages of microinverters appear to suggest that they would become more common. However, more than 99% of the PV solar systems installed worldwide are of the central inverter type (Novak, 2012). It is not known whether there is any microinverter based PV system installed anywhere in the Maldives as of 2014. Harb, Kedia, Zhang & Balog (2013) reported a comparative study of a microinverter and string inverter grid-connected 6 kW PV system. They used the reliability, availability, safety, failure, and cost of both configurations. They found out that the microinverter system gave an economic advantage as it was available more often; particularly when the high costs of replacing the string inverter was considered. The microinverter was found to offer safety advantages (particularly lack of arching) which were not monetized earlier. Lee and Raichle (n.d.) undertook a side-by-side comparison of micro and central inverters in shaded and unshaded conditions. They found that the microinverter system produced on average 20% additional power compared to the central inverter system in unshaded conditions. In partial shade conditions, the microinverter system produced on average 26% more power. Thus, it seems that the future of PV systems is in microinverter technology unless breakthroughs in central inverter technology take place.

Grid-tie Requirements

Recognizing the important role of PV power to mitigate global warming and reduce costs, most jurisdictions now allow customers to feed power into the grid. The quality control of grid power is paramount especially with the evolution of "smart grid" whereby among other possibilities, many producers may feed power into the grid. Power companies have stipulated technical requirements for grid connection. The overall authority is maintained by the relevant national body. In Australia, the requirements are given in Australian Standards AS 4777 and AS 5033. In the US the National Electric Code (NEC) Sections 690 and 705 give the technical requirements for interconnection and installation of PV systems. The requirements are long and much of the requirements pertain to safety. There are commonalities among various standards across the jurisdictions. For example, the total harmonic distortion of the grid-connected power waveform must be less than 5%. De-islanding is a requirement in all codes. Islanding is the feeding of power from the PV system into the grid while the grid is off-line causing hazardous conditions for workers and equipment. Usually de-islanding circuits are built into the inverter. These disconnect inverter output from grid in the event of loss of grid power. At the same time, the inverter will not energise any circuit de-energised by the grid.

For Maldives, JICA (2009) recommended guidelines for technical requirements for grid connection. There are different guidelines based on the power capacity of the PV system: namely, for less than 50 kW, less than 2 MW and less than 10 MW, etc. The guidelines were based on those of the Natural Resources and Energy Agency of Japan. For systems of capacity less than 50 kW, the JICA (2009, p. 8-18) seems to have been adopted in the Maldives. In summary, the guidelines of the Maldives Energy Authority (2013), the relevant body for standard setting in electric matters, are as follows:

(a) The frequency shall be 50 Hz. {Unlike the standards of other countries, no allowable deviation was stated}

(b) Depending on the PV system's output power, the breaker capacity and interconnection voltages are given as in the Table 3.

Table 3
PV System Categories by Breaker Capacity and Voltage

Category	Rated output of PV system (kW)	Breaker capacity	Interconnection voltage
1	< 7	40 A	LV (1Φ 230V)
2	7 – 35	63 A	LV (3Φ 400V)
3	35 – 175	315 A	LV (3Φ 400V)
4	175 >	—	MV (3Φ 11kV)

(c) For metering, the guidelines call for two (buying and selling) meters with protection for reverse rotation installed.

(d) With reverse power, the power factor at the receiving point shall be 85% or more seen from the grid side and should not be the leading power factor. Without reverse power, generating facilities must have a power factor of 95% or more.

When PV systems are connected to a grid, the voltage for low voltage customers shall be kept within 230 ± 5.75 V for 230 V lines and 400 V ± 10 V for 400 V three phase lines. When there is a danger of deviation from the normal line voltages for low voltage consumers due to reverse power, steps must be taken automatically to adjust voltage by using reactive power control function or output control function. If this is not possible, distribution line capacity must be increased.

(e) The following protection relays are mandatory: Over-voltage relay (OVR), Under-voltage relay (UVR), Over-frequency relay (OFR), under-frequency relay (UFR). If there is a possibility of reverse power, then a reverse power relay (RPR) must be installed at the point where such conditions can be detected. UFR, OFR and RPR shall be installed for each phase. Under and over-voltage relays shall be installed for all three phases.

(f) Self-synchronizing inverters shall be used to limit instantaneous voltage fluctuations to the lower limit of 207V on single phase lines. If external synchronizing inverters are used, the voltage fluctuations must be kept within 10% of the normal voltage; else, current limiting reactors shall be used to limit voltage.

(g) The following breakers shall be installed at the point of connection between PV systems power and grid parallel-off point: (i) power receiving breaker, (ii) PV system output breaker, (iii) generator communication breaker, (iv) bus communication breaker.

(h) One from each of the following active and passive methods of anti-islanding systems shall be used: Active (frequency shift type, active power fluctuation type, reactive power fluctuation type and load fluctuation type), Passive (power phase jump detection type, 3rd harmonic voltage rise detection type, frequency rate change detection type).

(i) If automatic recovery is enabled in the inverter, this function shall become active only after "receiving" voltage is confirmed to prevent the expansion of damage by unnecessary parallel-in.

(j) If PV system may cause overload to the grid (and hence substation transformers), the PV system must automatically limit the load or suppress feeding power into the grid.

The above technical requirements are similar to those in other countries as may be verified for NEC codes. In the next section, general evaluations of grid-tied systems are discussed.

Evaluations of Grid-tied Systems

A number of meta-analyses of grid-tied systems have been reported. For example, the International Energy Agency published a report of the issues faced with Australian, Austrian, British, Canadian, Dutch, German, Japanese, Spanish, Swedish, Swiss and US PV systems, including the German "1000 roofs programme", the Japanese programme for residential PV and "German Sun at school programme" (International Energy Agency, 2002). The study found inverter failures, over-rated power of modules, partial shading of the array, soiling, and faulty connections on the dc side were the main problems of PV systems. The report suggested the following maintenance regime: inspect arrays annually, clean arrays regularly and perform monthly check on power production. The study also noted that amorphous solar cells degraded most. The main cause of inverter damage was from surge voltages from the grid. The report also suggested using cage clamps for connections, providing drainage for all condensation in all outdoor boxes, always introducing wires from the bottom among other workmanship-related advice.

A more recent review of grid-connected PV systems was carried out by Eltawil and Zhao (2010) to summarize the technical and potential problems. Eltawil and Zhao (2010) noted that inverters were the weakest link in the reliability of the PV system, corroborating the findings of International Energy Agency (2002). They recommended that the inverter be over-sized by 60% to 100% in comparison to the PV system to increase the reliability of the inverter. The inverter should be operated at unity power factor. At high penetration levels, variable power factors were not recommended. They concluded that the effects of harmonics and active methods of anti-islanding and distributed generation need further research.

With regard to the type of inverter used in grid-connection, it appears that the transformerlss ones are better in terms of system efficiency. Díez-Mediavilla, Dieste-Velasco, Rodríguez-Amigo, García-Calderón, & Alonso-Tristán (2013) reported a comparative evaluation of two 100 kW grid-tied systems which differ only in the inverter used. They both were in the same geographical area, used the same type of PV panels, support systems and wiring. One facility used an inverter with an integrated transformer. The other inverter was transformerless. Their results, based on the case study, indicated that the transformerless inverter system performed better than the isolated system by a factor of 1.2% which in economic terms represented more than 2000 euros per year.

The review indicates that grid-tied PV systems are promising, reliable, and satisfactory for the Maldives. Long-term performance studies for Maldives are almost non-existent for the country. Emerging popularity of microinverters and technically advanced inverters are likely to increase the penetration of PV systems. In large islands, the penetration will be limited due to effects of clouds, shading and other intermittent causes. In June 2014, Germany produced more than 50% of its electricity from PV systems for the first time setting a record in PV penetration ("Germany produces half of energy with solar," 2014).

Trends in PV Systems and Focus of Research

A number of trends in PV systems are evident. The most significant is the cost of the system. The cost per 1000 Wp installed is now under 2000 euros in Europe (Gaube, 2014). This reduction in cost is further likely to stimulate demand for installations.

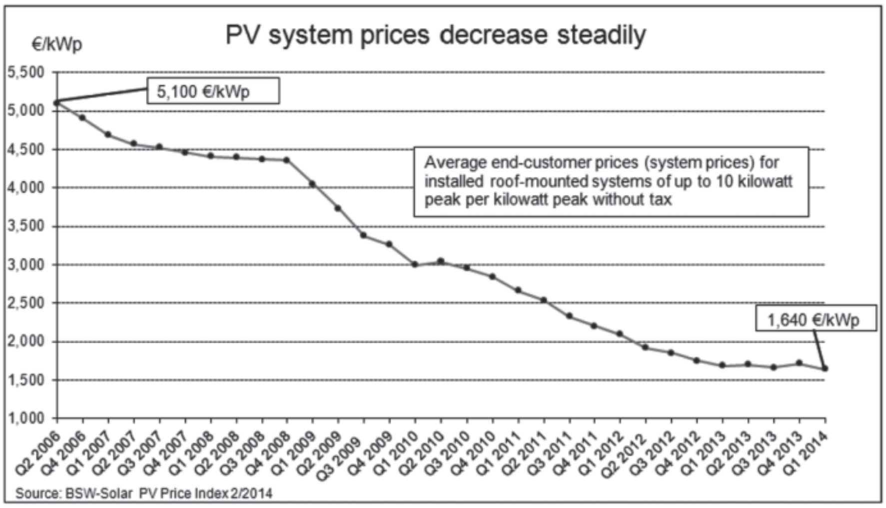

Figure 7. The cost of PV installations has been decreasing. In fact, in Germany, it is twice more expensive for homeowners to use grid electricity in 2014 than to generate solar power on their own roofs. Figure from Gaube (2014).

The reduction in cost of PV systems has led to greater investment in batteries. In fact, inverters with integrated lithium-ion batteries are now being offered by inverter manufacturers, for example, SMA Solar Technology. This development is partly due to lithium-ion battery technology becoming more common.

Two recent trends in PV systems had been earlier mentioned. They are the use of microinverters for PV systems and smart control. Smart control includes a number of technologies brought together. In homes, it includes the "smart" decision-making whether to use of PV power and grid power when a load needs electricity. In the field of arrays, smart control implies the control of a number of PV systems for maximum efficiency as in Thinadhoo PV systems mentioned earlier. In Kudahuvadhoo PV system, the "Solar Fuel Saver" technology controls the feed-in power of the solar plant by optimally interacting with the diesel generators. Solar Fuel Saver installed in Kudahuvadhoo is from juwi international GmbH. These technologies when combined with PV systems may be termed as "Smart PV Systems." However, the "smartness" may be an attribute of all and every major components of the PV system: smart PV arrays, smart inverters, smart batteries, smart grid and smart control.

In the smart PV system, according to Varadi (2013) who is one of the early chemists involved in PV cell development and once part owner of the largest PV cell manufacturing company—Solarex, there is another component which is an essential part of the smart PV system—storage. According to him, the smart PV system is "the combination of the "stand alone" and the "grid connected" systems. This "Smart" PV system is a combination of a PV system with electricity storage, an inverter and an "electronic brain" connected to the grid. He notes:

> This is actually a combination of the "stand alone" and the "grid connected" systems. The system operates as a "stand alone" system but if needed it becomes a "grid connected" system by selling or buying electricity. The decision is being made by the "electronic brain"… This new PV electricity storage and "electronic brain" will be the biggest selling product for the future. It will be used not only for small installations, but also for larger ones for businesses, such as department stores and so on (p. 1).

According to Varadi (2013), the advantages of the "Smart PV System" are such that it would be safe to predict that it will be the next step in the PV revolution. In fact, in Germany, the power companies have begun to sell storage systems to households. In California, a massive roll-out of distributed storage systems owned by households and third parties are taking place.

Focus of Future Research in PV systems

The future research will seek improvements in the performance of the key components of PV systems: PV panels, inverters, batteries and control systems. With PV systems, the focus is on increasing efficiency of PV cells while decreasing manufacturing costs. For inverters, research is required to increase efficiency (mainly switching components of H-bridge). Research is needed for improving battery technology, cycle times, longevity and power density.

With the widespread adoption of PV system and distributed storage systems in the low voltage grid, load management of the grid becomes a priority. The low voltage grid becomes essentially bidirectional with many households feeding power to the grid and others or the same households consuming it. Thus maintaining a balance between power generation and consumption becomes important. Imbalances become apparent as frequency deviations. For this reason, frequency-dependent power control of grid tied inverters will become necessary in the future. This will require subsystems to be coordinating the production and consumption of power optimally through improved algorithms and control mechanisms.

PV research requires much expenditure in terms of human expertise and materials. The PV companies are well placed to carry out that development work. In developing nations, like the Maldives, the emphasis of PV systems research must be on installation, performance, maintenance and socio-economic aspects. A PV research agenda in the Maldives may include the following:

1. Safety standards for installation of PV modules and components
2. Reliability and maintenance studies of various PV configurations
3. Low voltage grid reliability and penetration ratios
4. Further research on load modelling in small communities

5. Space utilization for PV infrastructure given the scarcity of land in the Maldives
6. Government subsidies for PV adoption and their impacts
7. Enabling factors and regulatory barriers for increased adoption of PV systems
8. Recycling and reuse of PV system components
9. Skill development in installation and maintenance of PV systems

In this review, the adoption of PV power in the Maldives was discussed from the early years until the end of 2014. An outline of irradiation data is followed by a discussion of PV systems in general with emphasis on various PV configurations and components with particular reference to grid-tied systems and their requirements. This is then followed by a discussion on evaluation of PV systems. Finally, from an outline the current trends in PV systems, a research agenda, and one suitable for the Maldives was drawn.

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