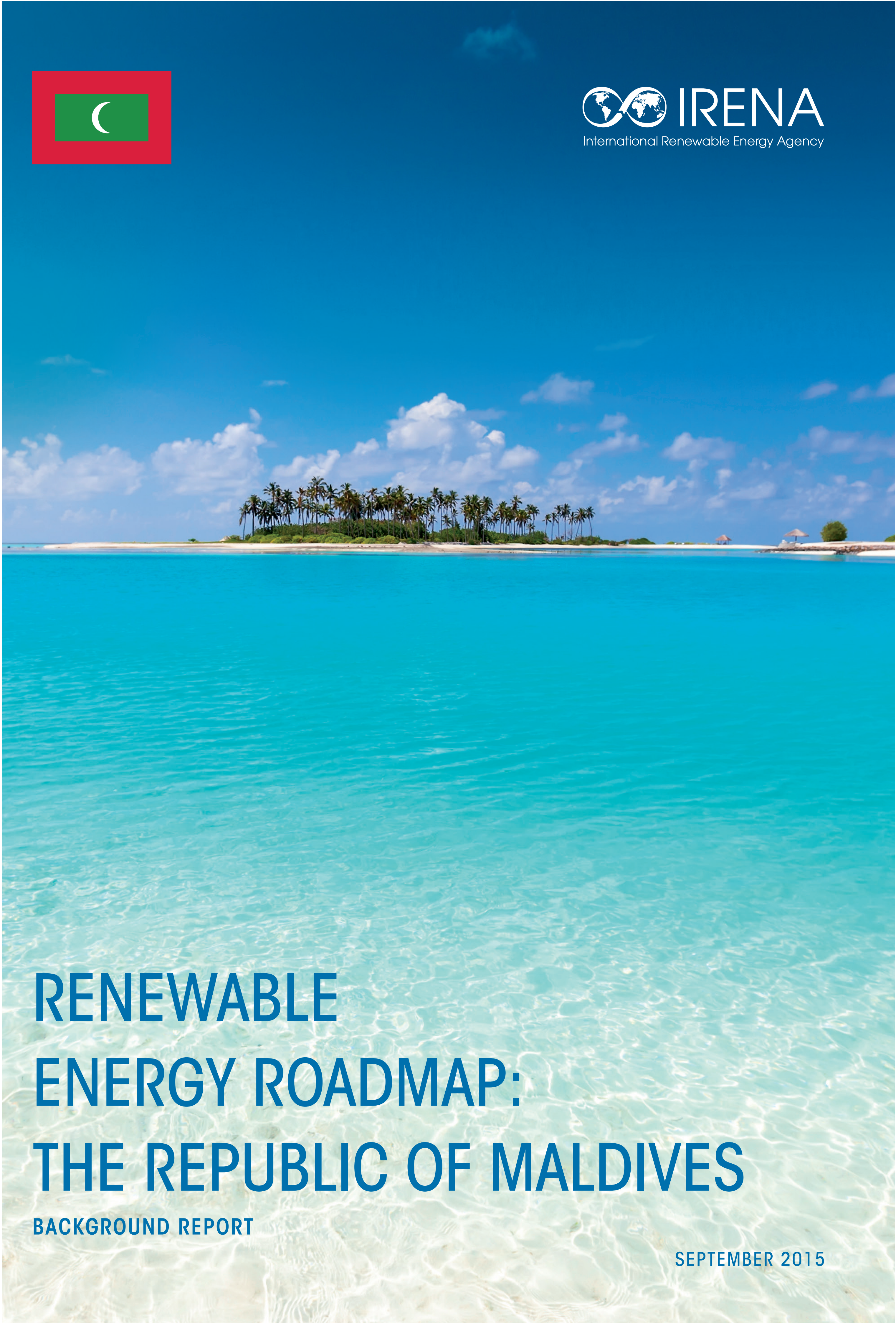

IRENA
International Renewable Energy Agency

RENEWABLE ENERGY ROADMAP: THE REPUBLIC OF MALDIVES

BACKGROUND REPORT

SEPTEMBER 2015

About IRENA

IRENA is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international cooperation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

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ADB	Asian Development Bank
IRENA	International Renewable Energy Agency
kV	kilovolt
kWh	kilowatt-hour
kWp	kilowatt-peak
LCOE	levelised cost of energy
MW	megawatt
MWp	megawatt-peak
OTEC	ocean thermal energy conversion
PV	photovoltaic
SIDS	Small Island Developing States
SoW	Scope of Work
SREP	Scaling Up Renewable Energy Programme
STELCO	State Electric Company
SWAC	seawater air conditioning
USD	US dollar
WACC	weighted average cost of capital

INTRODUCTION

This report has been produced by the International Renewable Energy Agency (IRENA) in response to an expression of interest by the Republic of Maldives for a renewable energy roadmap. During the initial phase of the roadmap analysis, IRENA conducted an extensive literature review of reports and studies relevant to renewable energy deployment in the Maldives. This review established that current studies provide the information needed to define a roadmap for deploying a high share of renewable energy in the Maldives.

The *Greater Malé Region Renewable Energy Integration Plan*, delivers a comprehensive review of energy in the Greater Malé region alongside an assessment of renewable energy resources and associated renewable energy technology deployment potential. It includes a technical and economic analysis of electrical interconnection options required in Greater Malé to support renewable energy deployment. The Asian Development Bank (ADB) report *Towards a Carbon-neutral Energy Sector: Maldives Energy Roadmap 2014-2020*, gives a renewable energy deployment plan covering the islands outside the Greater Malé region.

The *Maldives Scaling up Renewable Energy Program in Low Income Countries (SREP) Investment Plan* provides detailed information on major funding mechanisms and specific programmes created to support renewable energy deployment in the Maldives. The SREP report initiated the detailed planning process for deploying renewable energy in the Maldives, assessing potential and identifying funding.

The United States Agency for International Development (USAID) report, *Maldives Submarine Cable Interconnection Pre-feasibility Study,* gives detailed information including technical specifications, project timelines and cost estimates for undersea electrical interconnections. These will be essential for large-scale renewable energy deployment in Greater Malé and would assist with renewable energy deployment across the Maldives.

The Asian Development Bank (ADB) report *Solar PV Integration in Maldives*, seeks to determine the upper limit of photovoltaic (PV) into existing diesel-based solar electricity grids in the Maldives that can be economically and technically deployed. It provides specific PV deployment options and shows there is a substantial opportunity for PV deployment that does not threaten system stability or economic performance. The study states that in order to achieve economically and technically optimal PV deployment it will be necessary to adjust the current regulatory structure.

In this report, IRENA provides a summary of the key findings from each of the above studies and indicates how existing studies could be expanded or where results could be further reviewed. This report contains a complementary analysis of renewable energy deployment on the islands of Vilingili and Thinadhoo. This was undertaken to demonstrate how optimal levels of renewable energy deployment can be identified in each island of the Maldives. It offers a comparison with the renewable energy deployment potential identified in the studies reviewed. The overall objective of this report is to assist the Maldives in identifying optimal pathways for deploying a high share of renewable energy and suggest solutions to remove key barriers hampering deployment of the renewable energy options identified..

KEY RECOMMENDATIONS

The IRENA analysis generated the following key findings on renewable energy deployment in the Maldives:

- **Options currently identified do not achieve the full renewable energy potential in the Maldives.** The archipelago has significant renewable energy resources. If properly developed, these could greatly reduce dependence on imported fuel and lower the country's high electricity costs. However, the renewable energy options identified in current reports would not fulfil the total potential of renewable energy deployment. This report identifies several options that would increase renewable energy deployment potential and help overcome barriers to large-scale renewable energy redeployment in the Maldives.

- **Official renewable targets should be ambitious, achievable and clearly identified.** Official renewable energy targets should be based on analysis that identifies economically optimal and technically feasible renewable energy deployment options. It is also essential that these targets are clearly set out in official legislations or mandates and effectively communicated to all stakeholders.

  The government has most recently indicated a target to install renewable electricity generation that meets up to 30% of daytime peak load in all inhabited islands within the next four years. This is a significant reduction from the previously communicated aim for carbon neutrality and 100% renewable electricity by 2020. This new and lower target is probably well below the economically optimal deployment option for the Maldives and will not fulfil the full fuel import and cost reduction potential from renewables. It should be noted IRENA was not able to locate any policy documents that clearly and officially define the goals for renewable energy deployment.

  The government should undertake an analysis of economically optimal renewable energy deployment options. This would identify the key cost drivers, determine which technologies would be required and help work out the cost and performance trade-offs of a range of renewable energy targets. While developing renewable energy targets, it is critical that the government involves all relevant stakeholders to ensure feasibility of the targets and support for their implementation. These targets must be embodied in official legislation or mandates and clearly communicated to all stakeholders.

- **Renewable energy target setting and deployment planning needs to consider future demand growth.** IRENA analysis indicates that electricity demand is rapidly growing in the Maldives (especially in Greater Malé) and will likely continue to grow in the future. This increasing demand will need to be met with additional generation capacity, which should be focused on renewable energy. If demand growth is not taken into account, then the renewable share of generation will begin to fall as demand exceeds the capacity of installed renewable energy systems and must be covered by increased generation from diesel generators.

  To maintain or increase the renewable share in the face of rising demand, the energy planning process needs to look into the future and develop concrete plans for the deployment of additional renewable energy generation assets. This planning could be supported by a modular approach where renewable energy systems of a set size and configuration are installed at a regular interval. A modular approach could reduce the cost of and complexity of expanding renewable energy generation. The energy planning process should also take into account the maintenance and upgrading of renewable energy assets to ensure that they are operated properly and take advantage of the latest advancements in technology.

- **The Maldives has significant renewable energy resources to support electricity generation.** Solar PV has the highest generation potential in the Maldives and is relatively simple to deploy, operate and maintain. Onshore wind has the second highest generation potential after PV. Wind generation is more complicated to install and maintain but can produce electricity also at night when PV is not available. Renewable deployment in the Maldives should focus on these two established and cost effective technologies. The challenges of a large-scale PV and wind deployment in Maldives are addressed in this report.

Additional renewable energy generation can come from a number of local resources. E.g. anaerobic digestion of municipal wastewater can produce biogas for use in generators. This is an established and commercially available technology that can offset the electricity demand of wastewater treatment and deliver surplus electricity generation to the grid. In addition, most islands in the Maldives have easy access to deep water. As such, an analysis of ocean thermal energy conversion (OTEC) should be carried out to determine the potential and economics for this emerging renewable energy technology.

Other renewable energy technologies including offshore wind, concentrated solar, hydro, wave, tidal and geothermal either lack sufficient local resources or are too expensive to be deployed in significant capacity in the near future.

- **Deploying PV and wind can lower generation costs.** The Maldives power system is dependent on expensive imported diesel fuel, which results in high electricity generation costs. PV and wind can offer much lower generation costs. However, the cost of electricity from PV and wind is strongly linked to the cost of capital. To reduce generation costs through PV and wind deployment, the cost of capital for financing these systems must be kept as low as possible. Any factors that increase financial/project risk or raise borrowing costs threaten the ability of PV and wind to deliver cost-competitive electricity and thus make investments in renewable energy less attractive.

- **High shares of variable renewable energy can require electricity storage, flexible generators or other supporting measures.** The government should prioritise the deployment of PV and wind, which are the lowest cost renewable energy options based on local resources. Significant levels of PV and wind can be deployed without energy storage. However, because PV and wind generation are variable and not continuously available, achieving high shares of generation from PV and wind can require electricity storage, flexible generators or other measures to compensate for the variable output and provide electricity when there is no wind or sun. The specific limits on PV and wind generation that can be reached without the need for these measures are dependent on numerous factors and need to be evaluated on a case by case basis for each island.

  Energy storage, in the form of batteries, flywheels and other technologies, can support high levels of PV and wind generation. However, the cost of storage needs to be carefully evaluated. Given the strong demand for air conditioning, the Maldives could examine the use of ice storage, where excess PV and wind generation is used to produce ice that can later serve as a cooling source for air conditioning. Ice storage is generally a lower cost option version other technologies. Details of energy storage options can be found in the IRENA report *Renewables and Electricity Storage, a technology roadmap for Remap 2030*.

  Higher levels of PV and wind generation can be achieved by ensuring that current generators are properly maintained and operated in a manner that supports the integration of variable renewables. If it is determined that additional diesel units are required, a priority should be placed on flexible generators with low loading and fast response capabilities that support high shares of variable renewable energy.

  Other measures such as using the full features of PV and wind inverters, solar and wind forecasting and demand side management of deferrable loads such air conditioning, refrigeration and water pumping can provide lower cost alternatives for increasing the share of PV and wind generation and should be investigated. A detailed discussion of measures supporting variable renewables can be found in the IRENA report *Renewable Energy Roadmap for the Republic of Cyprus*.

- **Importing renewable fuels could significantly increase renewable energy generation.** High shares of renewable energy generation can also be achieved through the importation of renewable fuels. It should be noted that this option do not address energy security issues as fuel imports would still be required. However, importation of renewable fuels is one of the few cost effective options currently available that can support aspirational renewable energy targets such as the 100% renewable electricity goal envisioned in the climate neutrality policy.

If renewable fuels are to be considered, the simplest option would be importing biodiesel for use in existing diesel generators. These generators can operate on a blend of traditional diesel and biodiesel and operation using 100 percent biodiesel is possible. Biodiesel powered generators offer flexible generation that can support variable renewables such as PV and wind. The cost and operational implications of a switch to biodiesel would need to be closely examined.

Imported solid biomass provides another option, but would require the construction of new power plants with dedicated biomass boilers. IRENA research indicates that long-term contracts have been explored for importing solid biomass to the Maldives at prices that would make biomass generation cost-competitive with diesel and reduce volatility of electricity price through long term supply contracts.

- **Waste-to-energy generation options need to be carefully reviewed.** Waste-to-energy power plants offer an alternative supply of electricity that can offset diesel generation. However, waste-to-energy systems require extensive pollution controls that must be tightly monitored and well maintained, failure to do so can result in the release of toxic airborne pollutants. In addition, waste-to-energy generation requires an efficient waste collection and sorting system to ensure a reliable supply of waste with consistent properties that support energy conversion.

  Several of the studies reviewed for this report examine options for deploying of waste-to-energy systems in the Maldives. These options should be carefully reviewed to ensure that they account for the cost and complexity of operating and maintaining the necessary pollution controls and waste collection and sorting systems.

- **Non-electric renewable energy technologies can greatly reduce electricity demand.** Solar water heating, seawater air conditioning (SWAC) and solar air conditioning technologies provide significant opportunities to cut electricity demand in the Maldives. These technologies reduce the need to invest in additional generation capacity and boost the renewable energy share in end use sectors. They can reduce energy bills for hot water and air conditioning as they can be less expensive to operate than conventional systems using electricity from diesel generation. Solar water heaters are an established technology with global deployment and a clearly demonstrated ability to lower the cost of water heating. SWAC and solar air conditioning have a more limited deployment: projects using these technologies require case-specific feasibility studies to confirm that the systems can deliver cost competitive air conditioning services.

  A proposed SWAC project in Greater Malé is described in the New Energy Industrial Technology Development Organization (NEDO) report entitled *Multistage Deep Sea Water Utilization Infrastructure in the Republic of Maldives*. The government should thoroughly review the options identified in that study and consider further analysing the potential for solar water heating, SWAC and solar air conditioning. These technologies could play a key role in achieving a large-scale renewable energy deployment in the Maldives. An overview of these technologies, including case studies and cost estimations, can be found in the IRENA report *Renewable Energy Opportunities for Island Tourism*.

- **National energy policy should promote renewable energy deployment in resort islands and tourism facilities.** Power generation on resort islands is at least 100 MW and is almost exclusively dependent on diesel, although some investments in PV are taking place. This represents a significant proportion of installed generation capacity in the Maldives, where total publicly owned generation capacity is approximately 141 MW. Any policy aiming to significantly accelerate renewable energy deployment and reduce dependence on fuel imports should contain measures to incentivise private resort renewable energy investment. The IRENA report *Renewable Energy Opportunities for Island Tourism* can provide guidance on renewable energy deployment options for resort islands.

- **Renewable energy deployment potential is limited by policy and regulatory barriers.** The current policy and regulatory structure in the Maldives is not conducive to large-scale renewable energy deployment. A review of the current policy framework could help accelerate deployment. The current lack of regulations clearly supporting renewable energy increases the risk of investing in the sector. This raises capital cost and the competitiveness of renewable energy technologies.
- **Low data quality, lack of data and lack of access to data prevent quantitative-based, sound energy planning.** The planning necessary to support large-scale renewable energy deployment requires high quality data to be regularly collected and easily accessible to all stakeholders. The IRENA roadmap analysis encountered challenges related to the quality and availability of energy data in the Maldives. A comprehensive strategy should be adopted to improve data collection and handling to ensure all stakeholders have access to energy data required to support renewable energy deployment. The wealth of data and information built up by previous studies must be stored and made accessible so that it can support future energy planning efforts. Data collections should cover the areas outlined below at the very minimum.
    - renewable resource assessments
    - national and individual island energy balances updated annually
    - data on reliability and performance of present generation and grid assets including distributed, off-grid and renewable energy generation
    - hourly load data for each island
    - generator fuel consumption at a variety of loads for every unit
    - forecast of demand growth updated at least once a year (nationally and for each island, sector and end-use)
- **Supporting private renewable energy investment would greatly increase deployment potential.** Existing studies and reports only consider publicly owned and operated renewable energy systems such as PV on public roof space and wind farms on public land. If the full renewable energy deployment potential in the Maldives is to be fulfilled, supporting renewable energy deployment in the private sector is critical. This is especially true for PV in the Greater Malé region where a large amount of privately owned roof space has been excluded from the PV deployment options in existing studies.

  The government has indicated that a feed-in-tariff has been devised for renewables. It has also noted that all public utility companies have been instructed to purchase electricity generated from private installations and that power purchase agreements have been established to support these transactions. The government should closely monitor the impacts of its current efforts to support private renewable energy investment.

  The government should review the policy, regulatory and technical issues that would need to be resolved to support large-scale private investment in renewable energy, particularly PV. As part of this review the government should examine the support schemes and market mechanisms which have been developed to ensure that investors can achieve a reasonable return, while helping to reduce electricity cost for consumers. These include establishing a net-metering or net-billing mechanism or ensuring that regulations allow third party ownership or renewable energy system leasing.
- **Floating PV platforms could offer an additional deployment option.** The Maldives have an abundant solar energy resource. However, the deployment potential of ground and rooftop solar PV is limited by space constraints. Floating PV systems avoid these constraints by mounting PV panels on floating platforms that are anchored close to islands and connected to the electricity grid using undersea cables. It should be noted the floating PV is an emerging technology and does not have an established long-term performance or broadly based cost estimates. However, due to the severe land constraints faced in the Maldives the potential of this technology should be explored.

As of August 2015, two floating PV systems, one 15 kilowatt-peak (kWp) and the other 30 kWp have been installed at island resorts in the Maldives. An additional 100 kWp system is in the pipeline. The project developer claimed generation costs of less than 0.20 US dollars (USD) per kilowatt-hour (kWh), which is below present diesel generation costs in the Maldives. The developer estimates a 150 megawatt-peak (MWp) floating PV potential in the Maldives without the need for electricity storage. If storage is considered, additional deployment is possible.

Given the constraints of space on PV deployment, the government should assess the potential for floating PV and identify key challenges affecting widespread deployment of this technology. Floating PV could provide a significant share of electricity generation in the Maldives. However, it is essential that the cost, long-term performance and survivability of these systems be clearly established.

- **Electrical interconnection should be considered in the immediate future.** Large-scale renewable energy deployment in Greater Malé will require the islands of Malé, Villingili, Thilafushi, Gulhifalhu and Hulhumalé/Hulhulé to be interconnected using undersea electrical cables. Interconnections support renewable energy deployment by connecting islands with space available for renewable energy projects to demand centres like Malé, where there are serious space constraints limiting renewable energy deployment. Interconnections can also support renewable energy deployment on nearby uninhabited islands that provide some of the best sites for large-scale wind power deployment.

  The Ministry of Environment and Energy report *Greater Malé Region Renewable Energy Integration Plan* and the USAID report *Maldives Submarine Cable Interconnection Pre-feasibility Study* give a detailed analysis of options for undersea electrical interconnections in Greater Malé. The latter also examines interconnections in some outer island groups and between the Maldives, India and Sri Lanka. These detailed studies use energy balances and demand forecasts to determine technical specifications, cost estimates and project schedules for the proposed electrical interconnections. Both studies clearly show that interconnections would support significant increases in renewable energy deployment.

- **Including renewable energy in future infrastructure development plans.** The plans for expanding residential areas on Hulhumalé and Gulhifalhu provide an opportunity to deploy renewable energy at a significant scale. Including renewable energy as an integrated part of the infrastructure development plan, together with housing and commercial projects, would help to reduce the capital cost of PV and wind and support the deployment of large-scale projects like district cooling using SWAC.

- **Renewable energy for transport.** Successful large-scale deployment of renewable energy in the electricity sector will greatly reduce fuel imports to the Maldives. However, fuel for transport constitutes a significant proportion of imports to the Maldives. The Maldives should thus examine renewable energy options for transport and include these in medium to long-term national energy plans. Current options included electric vehicles powered by electricity from renewable energy. The short driving distances in the Maldives make it ideal for electric vehicles. However, large-scale deployment would significantly increase electricity demand and probably require the deployment of additional renewable energy systems. Biofuels imports are another option which could be used for land and sea transport. It is important to note that substantial energy use is linked to sea transport and international aviation, which deserve attention and further analysis, starting with detailed data collection.

LIST OF RELEVANT STUDIES COVERING THE MALDIVES POWER SECTOR

IRENA has identified the documents listed below containing important information relevant to deploying renewable energy in the Maldives.

- *Maldives SREP Investment Plan*, Ministry of Environment and Energy Republic of Maldives, October 2012
- *Greater Malé Region Renewable Energy Integration Plan*, Ministry of Environment and Energy Republic of Maldives, Phase I: Assessment of RE options for Greater Male Region, October 2014
- *Greater Malé Region Renewable Energy Integration Plan*, Ministry of Environment and Energy Republic of Maldives, final report, February 2015
- *Maldives Submarine Cable Interconnection Pre-feasibility Study*, USAID, April 2010
- *Towards a Carbon-neutral Energy Sector: Maldives Energy Roadmap 2014-2020*, ADB, 2014
- *Solar PV Integration in the Maldives*, ADB, January 2013
- *Report on Energy Supply and Demand 2008-2009*, United Nations Development Programme and Global Environment Facility, August 2010
- *Maldives National Energy Policy and Strategy*, Ministry of Housing and Environment, 2010
- *Multistage Deep Sea Water Utilization Infrastructure in the Republic of Maldives*, NEDO, 2011
- *Power System Expansion Plan for Gdh, Thinadhoo*, Ministry of Environment and Energy Republic of Maldives, May 2014
- *Technology Assessment Report*, Ministry of Environment and Energy Republic of Maldives, May 2014

Details of the key findings from the most important of the studies above are supplied in separate sections below.

SREP INVESTMENT PLAN

The following section consists of direct extracts from the Ministry of Environment and Energy's SREP Investment Plan and is intended to provide a clear overview of the structure and intent of the SREP programme in the Maldives. The SREP Investment Plan provides a clear basis for enabling the widespread deployment of renewable energy in the Maldives including funding to support specific renewable energy deployment programmes. To date it is not clear which of the projects identified in the SREP have been successfully implemented. In addition it is not clear whether the renewable energy deployment plans outlined in the *Greater Malé Region Renewable Energy Integration Plan* and other studies cited in this report are coordinated with goals and programs defined in the SREP, which is one of the primary funding mechanisms for deploying renewable energy in the Maldives. It is necessary to clarify the relationship between the SREP Investment Plan and renewable energy projects identified in these other studies. This distinction will help define a coherent national energy plan and associated policy and regulatory frameworks.

SREP Investment Plan objectives

The SREP Investment Plan's main objective is to transform the electricity sector through large-scale renewable energy deployment. This will benefit the Maldives and its people by generating economic opportunities, widening access to sustainable and reliable energy, supporting sustainable socio-economic development and contributing to poverty reduction. Investments in renewable energy technologies provide significant economic benefits. Not only do they displace high cost diesel fuel, but they also contribute to lowering the subsidies that accompany diesel-based electricity generation. The principles guiding the *Maldives SREP Investment Plan* agree with the strategic objectives of the 2010 National Energy Policy and Strategy:

- Enable an environment supporting the development of a reliable and sustainable energy sector and meet the constitutional obligation of the government to provide electricity to every inhabited island at reasonable standards commensurate to the island.
- Reduce national economic and energy sector dependence on fossil fuel by diversifying energy supplies and improving energy efficiency.
- Encourage the adoption of low-carbon technologies in energy production, distribution and consumption by promoting a healthy lifestyle.
- Exploit local energy resources and renewable technologies.
- Engage private enterprise in the development of the energy sector, energy services and quality assurance mechanisms.

SREP Investment Plan components

The SREP Investment Plan envisages investments of USD 139 million to support three SREP components:

Renewable energy for the Greater Malé region. This component is expected to require about USD 69.5 million with USD 35 million coming from the private sector as equity and debt to finance about 19 MW of renewable energy. This includes 11 MW solar PV for the capital Malé, 4 MW solar PV for surrounding islands that are part of the Greater Malé region and another 4 MW waste-to-energy in Thilafushi.

Renewable energy for outer islands. This component targeting the outer islands would finance full renewable energy in about ten islands with low electricity consumption and power system upgrades in about 15 islands to prepare them for large-scale renewable energy deployment. It would increase the share of renewable electricity to up to 30% of total generation in about 30 islands and will require about USD 62 million, with USD 16 million coming from the private sector.

Technical assistance and capacity building. This component will support the creation of an enabling environment for renewable energy investment and human capacity building. It will also fund project preparation and improved access to better quality and more comprehensive renewable resource data. The total resource allocation for the activities in this component is about USD 7 million.

SREP Investment Plan programmes

The above SREP components will be supported by the following four programmes:

Accelerating Sustainable Private Investments in Renewable Energy (ASPIRE). All projects in this programme will be based on a feed-in tariff with the use of appropriate guarantee instruments from the World Bank Group as a risk mitigation tool for leveraging private investments. It will also target a number of waste-to-energy projects. This programme consists of waste-to-energy for outer islands, solar PV for the Greater Malé region and solar PV/wind for 30 islands with medium or large electricity consumption. Preparations for renewable energy will be made on about 15 islands under the POISED programme (see below). The World Bank Group is the lead agency.

Preparing Outer Islands for Sustainable Energy Development (POISED). On the basis of the avoided cost of fuel, electricity generation from solar PV and wind in some locations is less expensive than energy generation from diesel. This programme will support full implementation of renewable energy systems on ten islands with low electricity consumption. It will equip the power systems for a 20-30% share of intermittent renewable energy on 15 islands with large and medium electricity consumption. This will be achieved by upgrading and refurbishing inefficient generators and other necessary adjustments. ADB is the lead agency.

Waste-to-Energy (Thilafushi). This programme will provide a waste-to-energy power generation facility with a capacity of up to 4 MW to replace the existing diesel-based power generator on the island. This is part of the broader Government National Solid Waste Management Policy adopted in 2008. The International Finance Corporation Private Sector Operations Department supports an integrated waste management project for the Malé catchment area as a public-private partnership. The *Maldives SREP Investment Plan* only considers the implementation of the waste-to-energy facility even though this is part of the larger-scale waste management solution including the collection, processing and disposal of waste in the Greater Malé region. The Private Sector Operations Department of the International Financial Corporation is the lead on this programme.

Technical Assistance for Renewable Energy Scale-up. These activities will help strengthen the enabling environment and human capacities and identify additional renewable energy investment opportunities and data collection. ADB and the World Bank will each lead on technical assistance as appropriate.

Investments under the *Maldives SREP Investment Plan* will result in the installation of 26 MW of renewable energy generation. This means an annual reduction of around 56 000 metric tonnes of carbon dioxide emissions and about 22 million litres of diesel. The *Maldives SREP Investment Plan* work supporting these goals is expected to last five or six years. The 26 MW in the SREP Investment Plan would not be enough to achieve full renewable energy deployment potential. Options to resolve this are discussed in the conclusion to this report. The 26 MW in the SREP Investment Plan does not clearly line up with the 43.5 MW in renewable energy deployment envisaged in the *Greater Malé Region Renewable Energy Integration Plan.* The government should take decisions to reconcile these two key studies and define a clear, ambitious and achievable plan that represents the official roadmap for renewable energy in the Maldives.

GREATER MALÉ REGION RENEWABLE ENERGY INTEGRATION PLAN PHASE I

This integration plan, developed by the Ministry of Environment and Energy focuses on power generation in the Greater Malé region and is split into two reports. The first report, Phase I: Assessment of RE options for Greater Malé Region was published in October 2014. This report assessment of renewable energy options is based on a detailed review of the existing power sector, future demand estimations, analysis of local renewable energy resources and a review of low cost renewable energy technology options. This initial phase of the integration plan also includes a basic review of the local policies, regulations and institutional frameworks relevant to renewable energy deployment. These findings are summarised in this section. The integration plan's final report was published in February of 2015 and is reviewed in the next section of this roadmap. The final report focused on deploying electrical interconnections between islands in Greater Malé to support the renewable energy options identified in the initial phase of the integration plan.

The initial phase of integration plan analysed the following renewable energy technologies and associated resources: PV, onshore and offshore wind, biomass, tidal and OTEC. PV and onshore wind were found to be the only cost-effective renewable energy options for Greater Malé. The other technologies were not considered viable due to lack of local resources, high cost or lack of proven deployment. The specific reasons for excluding each of these technologies are explained below.

Renewable energy technologies excluded

Offshore wind. The report finds little potential for offshore wind in the Maldives, noting: "the seas around the islands are very deep and the slopes of the atoll are very steep. As a result there is little opportunity to place any wind turbines offshore from the islands". It also notes: "there is a possibility of placing turbines within the lagoons of the islands but this will increase the cost of construction by quite a margin. Also the lagoons are fairly small in area."

Concentrated solar power. Land constraints and other factors are noted as reasons for excluding concentrated solar power from the mix of renewable energy options. The report states "The solar thermal technology is still evolving and requires larger capacities to have economies of scale. Given the large area requirement for these technologies and the shortage in land availability in the Greater Malé region, concentrated solar power as a technology would not be suitable for deployment. Hence, solar PV technology has been considered for assessing the solar potential in the region."

Biomass. The report notes that the combined biomass potential of all islands in the Maldives is quite low due to very limited land availability. The report notes "As per the SREP Report, 2-5 MW of potential exists in Maldives owing to limited land mass and the low fertility of its coral soils. Hence, for biomass based power generation to take shape in Maldives, large quantities of biomass may be required to be imported, possibly from other countries in South Asia." The report examines the possibility of importing biomass, but only from India and Sri Lanka, and concludes: "it will be a challenging task for Maldives to import biomass and ensure long term biomass fuel contracting to mitigate the price volatility. In addition to this, the transportation cost will be another factor that will impact the viability of biomass power project (based on imported biomass fuel). Based on the above, it is proposed that biomass may not be considered as an option for meeting the electricity requirement in Greater Malé region till adequate framework is in place to ensure long term fuel supply and mechanisms to mitigate fuel price volatility risk."

Land availability limits the deployment potential for established low-cost renewable energy technologies like PV and onshore wind. This means sustainably harvested biomass appears to be one of the few options currently available to reach a very high share of renewable energy in the Maldives. IRENA analysis to date indicates that long-term supply contracts for biomass can be obtained at costs that would allow renewable power generation below the present cost of diesel-based generation.

The government may thus wish to conduct a deeper analysis on the cost of building large-scale biomass power generation plants and securing long-term biomass import contracts. It should be noted while this option could increase the renewable energy generation it would not address energy security concerns as fuel imports would still be required.

Ocean energy. The report provides a brief overview of tidal and OTEC but notes: "given the lack of technical studies undertaken in Maldives and limited commercialisation, these technologies have not been considered as a possible option under least-cost plans for meeting electricity requirements in the Greater Malé region." The government may wish to conduct additional analysis to determine the future potential of ocean energy technologies in the Maldives. In particular, SWAC systems are becoming popular in islands with substantial cooling load associated with tourism (see IRENA, 2014). A project is already under consideration for HuluMalé. Exploring the potential on other islands with large cooling loads in the Greater Malé region, especially Malé, might be worthwhile. Although SWAC does not produce electricity, it reduces the electricity demand for cooling, contributing to the overall renewable energy deployment. A cost estimate and an evaluation of the OTEC resource could also be warranted to determine its potential as a baseload renewable energy option for future deployment once the technology is commercially available.

PV and wind deployment potential

The report concludes that PV and wind are the primary renewable energy technologies that can be cost-effectively deployed at a significant level. However, land availability places significant restrictions on both technologies.

Due to land constraints and buildings ownership concerns, PV deployment in the integration plan was restricted to a limited number of rooftop systems. As an example of these limits, figure 1 shows the buildings considered for PV deployment outlined in black. This clearly excludes the vast majority of roof space on the island. Similar limits were placed on other islands in

Figure 1: Proposed PV deployment on Malé highligted in yellow

Table 1: Greater Malé PV and wind potential

Island	Potential renewable energy capacity (MW)	
	PV	Wind
Malé	5.113	0
Hulhumalé	5.238	0
Villingili	0.578	0
Thilafushi	4.09	20
Hulhulé	6.581	0
Gulhifalhu	1.916	0
Total	43.516	

Greater Malé. No deployment in shallow water or lagoon areas is considered.

The study also included land constraints in the decision to limit wind power development to the island of Thilafushi, which is dominated by industrial development. A detailed analysis was performed on the basis of these land constraints to determine the maximum PV and wind power capacity that could be deployed in Greater Malé. The results are in table 1.

In addition to the 20 MW wind project listed in table 1, the integration plan mentions the possibility of a single 2 MW wind turbine on Villingili as well as four wind projects. These would be located on islands in the Malé Atoll 5-12 km away from the islands of Greater Malé and would have a cumulative capacity of 80 MW. These four 'near outer island' wind projects would require undersea electrical cables. No detailed analysis is given for any of these potential projects. The 'near outer island' wind generation of around 80 MW could be added to the 43.5 MW of renewable energy deployment identified in the integration plan. Nevertheless, this would not be enough capacity to fulfil full renewable energy deployment potential in the Maldives. Options for increasing renewable energy deployment are described in the following sections.

Additional renewable energy deployment options: private PV

Expanding PV deployment beyond the public roof space could greatly increase renewable energy deployment potential in the Maldives. This is especially true for the Greater Malé region where there is a large amount of privately own roof space. A detailed investigation is required to work out the proportion of existing roof space that can support PV. Shading from other buildings and competing uses for air conditioning condensers or antennas are among the potential factors to take into account.

Existing studies limit their estimates of PV deployment potential to installations on publicly owned buildings. For example, the main island of Malé has a surface area of approximately 1.9 million square metres, the majority of which is covered by buildings. However, the *Greater Malé Region Renewable Energy Integration Plan* only considers PV deployment on 36 520 square metres of roof space (less than 2% of land area). This results in an estimated PV capacity of 5.115 MWp as shown in figure 1.

A rough estimation by IRENA shows that using 25% of the Malé land area for PV deployment would result in around 62 MWp of PV capacity. This compares to 66 MW of diesel generation currently installed. Similar increases on the other island of Greater Malé may also be possible. Supporting the deployment of PV on private roof space could thus greatly increase renewable energy deployment potential.

The current feed in tariff and other programmes supporting private renewable energy investment need to be closely monitored to ensure they are effective. The government should examine current policy and regulation to identify any barriers a large-scale private investment in PV. Key concerns include regulations and grid codes that allow privately owned renewable energy generation to be easily and cost-effectively connected to the grid. Support schemes/market mechanisms allowing private owners to recover investment costs/generate a profit are another issue. These could include, net-metering net-billing or rules allowing third-party ownership and leasing. Large-scale PV deployment would support local job creation. However, this will require the development of local capacity for PV installation and maintenance.

The Addu High School PV project, winner of the 2015 Zayed Future Energy Prize, is a potential model for expanding rooftop PV deployment in the Maldives. The government should examine this system to see if it could provide a replicable model for other buildings in the Maldives.

Additional renewable energy deployment options: floating PV

Floating PV platforms are another option for increasing PV deployment. These systems mount PV panels on floating platforms moored close to islands and connected to the island's grid using an undersea cable. Swimsol GmbH, a private PV developer, has installed two floating PV systems in the Maldives, with capacities of 15 kilowatt-peak (kWp) and 28 kWp, and is also rolling out a four-platform, 100 kWp system. Floating PV systems would eliminate many of the concerns relating to limited land availability. In addition, the Swimsol projects have demonstrated a generation costs of less than USD 0.20/kWh for floating PV, which is below the present diesel generation cost in the Maldives.

It should be noted the floating PV is an emerging technology that does not have an established long term performance or broadly based cost estimates. However, due to the severe land constraints faced in the Maldives the potential of this technology should be explored.

However, floating PV does introduce some additional challenges compared to traditional rooftop or ground-mounted PV. For example, installing undersea electrical cables creates additional logistics. Furthermore, floating PV platforms have to be placed in areas with low wave activity to ensure they survive. For example, Swimsol indicates that its current system can survive waves up to 1.5 metres in height, the maximum wave height it has estimated for the centre of lagoons in the Maldives.

Swimsol analysis indicates the potential for 150 MWp of floating PV in the Maldives without the need for long-term battery storage, and a larger potential if battery storage is included. This compares to national diesel generator capacities of approximately 141 MW on inhabited islands and 100 MW on resort islands. This analysis needs to be carefully checked but indicates that floating PV could greatly increase renewable energy generation potential in the Maldives.

Given the major limits to land available for PV deployment, the government should consider a detailed analysis to assess floating PV potential and identify key challenges affecting the widespread deployment of this emerging technology. This analysis could include several floating PV pilot projects that would define the key deployment, operation and long-term survivability issues.

Limits to renewable energy deployment models

The PV deployment analysis in the integration plan uses detailed hourly irradiance data to calculate PV generation potential in megawatt-hours. However, PV deployment potential in MW from table 1 is based exclusively on an estimation of the physical area available for PV panels. The integration does not include any analysis of the economically optimal amount of PV deployment or the impact of PV generation on electricity tariffs. In addition, technical limits to integrating variable renewable energy technology like solar PV and wind are not considered. Meanwhile, energy storage requirements to facilitate PV integration are not assessed.

The integration plan analysis for wind deployment is more sophisticated, using a HOMER model on the proposed Thilafushi wind project. However, it is not clear whether energy storage was included as an option in this model.

IRENA has performed an economic optimisation of PV deployment on the island of Villingili and Thinadhoo, including battery storage, based on a HOMER model. The IRENA analysis took land constraints into account but showed that economically optimal PV deployment in Villingili would exceed the 0.6 MW found in the integration plan. IRENA also showed the use of energy storage was part of a least-cost option due to the substantial difference in generation cost between PV and diesel. This means a certain amount of storage cost is recovered. The results of the IRENA analysis are described in an annex to this report.

Key steps to supporting renewable energy deployment

The integration plan notes that no wind power projects have yet been deployed in Greater Malé, and provides a detailed analysis of the challenges to deploying wind power in the Maldives. For instance, the integration plan notes "component weight and blade length may be a significant constraint on deployment in the Maldives. The logistics of delivering the turbine components to the site and then erecting them need to be carefully assessed as part of a detailed feasibility study." To overcome the challenges identified, the report provides the following key steps to be taken before deploying any wind projects:

- Install an 80 metre wind measurement mast at the western end of Thilafushi and measure the wind for at least 12 months.
- Put a suitable management system in place to specify, install, operate, maintain and protect the quality of the wind data measurements.
- Carry out a suitable geotechnical study throughout the area planned for a wind farm on Thilafushi.
- Carry out a logistical study to identify any constraints on the size and weight of wind turbines that can be accepted by the relevant port.
- Carry out a logistics study to ensure that all plant and equipment can be transported from the port to the site.
- Carry out a study to determine the best options for delivering and using a suitable crane to erect the turbines.
- If wind energy is chosen for the Greater Malé region, a detailed feasibility study should be undertaken for a 10–20 MW wind farm consisting of five to ten turbines of 2 MW each on Thilafushi.
- It is recommended that the project contractors provide adequate operations and maintenance training for Maldivian technicians on the turbine and balance of plant installed.
- It is recommended that a budget for at least five years of operation and maintenance on the turbines and balance of plant is provided within the warranty operating and maintenance contract.

The integration plan does not give any specific details on how the proposed PV systems can be deployed nor does it detail the challenges that might be encountered. The government needs to investigate the barriers to PV deployment in the Maldives and devise a comprehensive plan to overcome them. This report highlights some of the key barriers and proposed solutions that will help to accelerate PV deployment.

Waste-to-energy

The integration plan also examines waste-to-energy power generation based on municipal solid waste incineration and shows a potential for 8 MW of waste-to-energy capacity on the Island of Thilafushi by 2025. If this option is pursued, extreme care should be taken to ensure that adequate pollution abatement equipment is installed and properly maintained. This is because municipal solid waste incineration generates harmful pollution. It is crucial to combine state-of-the-art abatement technologies (*e.g.* high-temperature flue gas treatment to abate dioxins and furans) and proper operations and maintenance practices. In addition, the definition of waste-to-energy as a renewable energy technology is questionable, especially in the Maldives. This is because the biomass fraction in the waste stream in this island group is limited due to restricted vegetation.

The study does not cover some established renewable energy sources for waste-to-energy power generation such as biogas generated at wastewater treatment facilities. This established and commercially available technology warrants feasibility studies wherever wastewater treatment is present in the Maldives.

Policy and regulatory barriers

The integration plan notes that the "growth prospects and level of commercialisation in the wind and solar sector is inspiring and promising." But it points out that "these sectors are not at par when it comes to policy and regulatory framework in the Maldives. The policies spanning these sectors need to be well laid out and centred towards promoting capacity expansion." As a result "initial pilot projects in the Maldives have met with mixed success as appropriate enabling environment was missing."

The plan notes that "lots of barriers have been addressed by the ministry such as implementation of a standardised PPA under the ASPIRE project, development of a new renewable energy policy etc." But it points out several specific issues to be resolved to promote large-scale renewable energy before deployment can take place. These are outlined below.

- Policies and programmes need to be identified and implemented that improve the ongoing operational structures governing the renewable energy markets.

- Industrial policy action for promoting solar and wind manufacturing should be encouraged.
- Lack of regulatory provisions such as provision for third party sales etc.
- Lack of policy targets for different renewable energy technologies.
- Lack of tariff structure for renewable technologies.
- The power framework needs to be evaluated, and long-term clarity is needed on interconnection guidelines.

The study suggests the following policy recommendations to overcome the barriers listed above:

- policies mandating quantities or prices for renewable energy
- policies reducing renewable energy investment costs to incentivise renewable energy deployment
- policies reducing market barriers and facilitating renewable energy markets such as direct public investments in renewable energy

The IRENA review has also concluded that renewable energy policy and regulation are key concerns. It is recommended that the government performs a full review of the energy policy to identify specific areas preventing or holding back renewable energy deployment.

Interconnection

The integration plan notes that undersea electrical interconnection will be necessary to achieve the following aims:

- meet electricity demand on the main island of Malé which has run out of space to build additional thermal generation
- achieve full renewable energy deployment potential by connecting renewable energy generation assets on islands with low demand to the demand centres on Malé and other populated islands
- support potential wind projects on "near outer islands" in the Malé atoll

Interconnection analysis is covered in the *Greater Malé Region Renewable Energy Integration Plan* final report reviewed in the following section.

GREATER MALÉ REGION RENEWABLE ENERGY INTEGRATION PLAN FINAL REPORT

As noted above, the *Greater Malé Region Renewable Energy Integration Plan* was developed in two phases. An initial phase assessed renewable energy deployment options in Greater Malé and has been summarised in the previous section. This section examines the findings of the integration plan final report delivered to the government in February 2015. It analyses electrical interconnections between the islands in Greater Malé and considers how such projects could support the renewable energy options identified in the initial phase of the integration plan. The final report does not consider how interconnection could support the deployment of additional renewable energy options beyond those identified in the initial phase of the integration plan. The government will thus need to carry out further analysis to examine low-cost pathways for additional renewable energy deployment and determine how this would affect the proposed electrical interconnection strategy.

Justification for electrical interconnection

The integration plan final report first considered each island of Greater Malé in isolation and worked out how much new diesel generation would be required to meet demand growth to 2020. It also used grid stability studies to determine whether the renewable energy options identified in the initial phase of the integration plan could be safely integrated into each island's grid. The results of this analysis are shown in tables 2 and 3. A project is in progress to electrically interconnect the islands of Hulhumalé and Hulhulé in 2015. The final report analysis assumes the successful completion of this project and treats Hulhumalé and Hulhulé as a single electrical system.

Table 3 shows demand growth to 2020 will result in generation capacity deficits in case of a major generation unit outage on all islands in Greater Malé except for Thilafushi. This is a serious concern as space constraints will probably prevent additional generation capacity deployment on Malé. The report argues that interconnecting the islands would allow additional generation capacity to be installed on other islands to meet growing demand in Malé.

Table 3 gives the results of grid stability analysis carried out on each island in isolation and clearly shows that interconnections would greatly increase the renewable energy deployment potential in Greater Malé. This is another strong argument in favour of electrical interconnection as a necessary component of the Maldives strategy to expand renewable energy

Table 2: Greater Malé region generation balance for 2020

	Malé	Hulhumalé and Hulhulé	Thilafushi	Villingili	Gulhifalhu
Projected 2020 demand (MW)	72.5	19.5	0.9	2.4	3
Existing generation capacity (MW)	61.42	5.6	1	2.8	0.121
Planned generation capacity additions (MW)	13.53	6	4	0	0
Total generation capacity (MW)	74.95	11.6	5	2.8	0.121
N-1 generation capacity: outage of major unit (MW)	66.22	9.6	4	1.8	0.067
Surplus (+)/deficit (-) (MW) for N-1	-6.28	-9.9	3.1	-0.6	-2.933
Additional generation required (MW)	8	16	3.1	1	3.6

Table 3: Comparison of 2020 renewable energy deployment potential and grid stability constraints

	Malé	Hulhumalé and Hulhulé	Thilafushi	Villingili	Gulhifalhu	Total renewable energy potential
Solar PV potential (MW)	5.113	11.819	4.09	0.578	1.916	43.516
Wind potential (MW)	-	-	20	-	-	
Grid stability limit – solar PV (MW)	5.113	8	0	0.578	1.2	14.891
Grid stability limit – wind (MW)	-	-	0	-	-	

deployment. IRENA strongly endorses the report findings that interconnection will be necessary for large-scale renewable energy deployment.

Grid stability analysis does not appear to include additional renewable energy assets beyond those identified in the initial phase of the grid integration plan, with the exception of Malé. For Malé, the final report remarks that a total PV capacity of 20 MW could be safely integrated into the existing grid without interconnection. This represent an additional 14.887 MW over the capacity identified in the initial phase of the integration plan. As noted in the previous section, the renewable energy deployment potential given in table 3 is significantly constrained by limiting PV deployment to publicly owned roof space. The government should determine if the integration plan grid stability analysis showed that higher PV integration is possible on the other islands. This could should that greater PV deployment is possible before electrical interconnections are completed.

Interconnection supporting renewable energy deployment

The *Greater Malé Region Renewable Energy Integration Plan* final report gives a detailed analysis of several options for interconnecting the islands of Greater Malé. This would use a variety of undersea cables, underground and overground lines and electrical substations. This analysis considers a three phase approach described below:

Phase 1 (2016-2020): Malé interconnection with Hulhumalé and Hulhulé using 132 kilovolt (kV) lines, and Thilafushi interconnection with Gulhifalhu and Villingili using 11 kV lines.

Phase 2 (2020–2025): Thilafushi interconnection with Malé with alternatives for both 11 kV and 132 kV lines. Phase 2 would fully interconnect all islands in Greater Malé.

Phase 3 (beyond 2025): Thilafushi interconnection with Hulhumalé using a 132 kV line to support a 150 MW natural gas generation plant on Thilafushi.

For each phase of proposed interconnection, the final report provides a technical study covering load flow and transient stability. This determines the how the system will perform and what amount of renewable energy generation can be integrated. Table 4 shows how the phase 1 interconnections increase renewable energy deployment potential.

Phase 2 interconnections would support the deployment of the full 43.516 MW renewable energy potential

Table 4: Increase in renewable energy deployment potential with phase 1 interconnection

	Solar PV potential (MW)	
	No interconnection	Interconnection
Malé – Hulhumalé & Hulhulé	13.113	16.933
Thilafushi – Gulhifalhu -Villingili	1.78	2.52
Greater Malé total	14.893	19.453
Additional capacity	–	4.56

identified in the initial phase of the integration plan, primarily by connecting the main demand centre of Malé with Thilafushi. This allows the 20 MW wind project and an additional 4.09 MW of PV to be deployed. Phase 3 would add significant interconnection capacity in support of a 150 MW natural gas power plant proposed by STELCO to replace existing diesel generation assets.

As noted above, the interconnection analysis does not specifically examine how interconnection could support renewable energy deployment beyond the limits set in the initial phase of the integration plan. Also, this analysis does not appear to consider how interconnection would allow existing diesel generation units to be optimised to increase their efficiency or to support a higher share of renewable energy. In addition, the grid stability analysis employed to determine the increased renewable energy deployment through each phase of interconnection does not appear to examine any additional measures to support renewables integration. This could include, for example, advanced inverters, solar or wind forecasting, electricity storage and demand-side management.

IRENA strongly recommends that the government carries out additional analysis of proposed interconnection options to find out whether they are sufficient to support greater renewable energy deployment. Interconnection projects are capital-intensive and should run for decades. It is thus essential that the interconnections are designed to support future renewable energy deployment. Deploying a lower-cost interconnection now could create a bottleneck limiting future renewable energy deployment and requiring another round of interconnection design, financing and construction.

Interconnection implementation plan

The final report contains a detailed interconnection implementation plan. This includes a proposed schedule developed in a Gant chart with project milestones, an economic analysis, an environment and social impact analysis and an examination of capacity building.

The final report's economic analysis gives cost estimates for each proposed phase of interconnection deployment. The cost for the combined phase 1 and 2 interconnections is around USD 85-165 million. These phase 1 and 2 interconnections would together allow the full renewable energy potential identified in the integration plan to be deployed. The final report estimates a net present value of savings amounting to USD 92 million. This results from the additional 35.32 MW of renewable energy assets supported by the interconnections (the amount exceeding that which could be deployed without interconnection). These savings are based on a very simple levelised cost of electricity estimate and should be reviewed. The economic analysis also offers a top level review of the various options available to help finance the interconnection projects.

Phase 3 is envisaged primarily to support a proposed 150 MW natural gas power plant on Thilafushi. This would replace all the current diesel generation assets. It would require significant additional interconnection capacity between Thilafushi and Hulhumalé amounting to 132 kV. The final report does not offer any insight into how this additional capacity would support renewables deployment but it would undoubtedly increase renewable energy deployment potential. IRENA advises caution on this issue. While the interconnection analysis shows the 150 MW natural gas plant is feasible, there are major questions on the cost, system security impacts and concentration of limited investment capital into such a large-scale project. IRENA would recommend that any study examining this proposed project should include a direct comparison to an equivalent investment in renewable energy.

The final report includes a brief look at the potential environment and social impacts of the interconnection projects. This review highlights the relevant laws and regulations that would be impacted or require changes and examines potential mitigation measures for environmental impacts.

The capacity-building section notes that the current skillset at STELCO is mostly sufficient to deal with operation and maintenance of undersea electrical interconnection. However the report notes that the use of 132 kV lines not used in the Maldives at present means "STELCO personnel employed in 132 kV substations would have to be trained in various aspects of the 132 kV system including technical issues like the bus switching scheme, protection and control as well safety precautions."

As far as the 132 kV line is concerned, the final report also notes: "in the Maldives, the Maldives Energy Authority, which is affiliated to the Ministry of Environment and Energy, Maldives, has a broad mandate covering development of the technical code and standards, regulating the market etc. The involvement of the regulator will be important for formulating technical codes and standards, system operating procedures etc. for the introduction of the 132 kV voltage level. In addition, the Maldives Energy Authority will have to review the commercial mechanism for the interconnected grid."

The IRENA review of the *Greater Malé Region Renewable Energy Integration Plan* final report indicates it provides an in-depth analysis of one possible pathway for deploying interconnections in the Maldives. IRENA agrees that interconnections are needed to provide additional generation capacity for Malé and support the deployment of renewable energy in Greater Malé. However, the *Greater Malé Region Renewable Energy Integration Plan* does not provide a strategy for deploying the identified renewable energy options. Details are given only for the interconnection projects.

In addition, large-scale renewable energy deployment is not analysed. While the renewable energy options identified do reduce diesel fuel consumption, they are too limited to prevent the need for investment in additional diesel generation capacity. As a result, the share of renewable energy generation continues to fall over the period of the study, and demand and diesel capacity increase.

IRENA recommends that the government uses the interconnection options identified in this study as a basis for additional analysis focusing on how interconnection can support a least-cost option for large-scale renewable energy deployment. An additional interconnection study summarised in the following section can also provide input into this expanded analysis.

MALDIVES SUBMARINE CABLE INTERCONNECTION PRE-FEASIBILITY STUDY

This USAID report gives a detailed analysis of options for undersea electrical interconnection in both Greater Malé and some of the outer islands and examines options for connecting the Maldives to India and Sri Lanka. This highly detailed study uses energy balances and demand forecasts to work out the technical specifications required for the proposed electrical interconnections. The report contains specific recommendations on when and where to build electrical interconnections and includes estimates for the associated project costs.

Given the necessity for interconnection highlighted in the majority of renewable energy studies about the Maldives, this study should be reviewed, in particular to inform the expansion plan for power generation in the Greater Malé region. It should be noted that this study was produced in 2010. This means it might be necessary to examine some of the assumptions relating to electricity demand growth to ensure the proposed interconnections have sufficient capacity.

TOWARDS A CARBON-NEUTRAL ENERGY SECTOR

In this study, the ADB gives a comprehensive plan, cost estimates and project timelines for deploying a high share of renewable energy systems across the majority of the islands outside the Greater Malé region. The report *Towards a Carbon-neutral Energy Sector: Maldives Energy Roadmap 2014-2020* details an ADB project aiming to assist in the deployment of hybrid power systems. These would make use of PV, wind and diesel generation combined with battery storage to achieve high levels of renewable energy on 134 outer islands outside the Greater Malé region. The report provides the following:

- high-level evaluation of Maldives energy balance
- basic overview of relevant policy and regulatory issues
- simple renewable energy resource assessment covering large regions
- analysis of inefficiencies in existing diesel-based power systems
- top level review examining which renewable energy technologies are best for outer island deployment
- more detailed analysis of the optimal hybrid system for each island, described below

Outer island hybrid power systems

The report proposes three different models for hybrid systems to be deployed in the outer islands:

- lower renewable energy penetration (<10% annual generation) with no energy storage for four islands with greater population and energy demand
- systems with 10-80% annual renewable energy generation and lithium-ion batteries for the majority of the outer islands (120 out of134)
- systems with 80-100% annual renewable energy generation and lead-acid batteries for ten islands with small populations and low power demand

Estimates are provided for project funding and timelines for proposed system deployment on all 134 islands, broken down into three phases:

Phase 1: pilot projects on five islands to be completed in 2015

Phase 2: projects on 60 islands to be completed in 2016

Phase 3: projects on 69 islands to be completed in 2017

The report specifies that the ADB project has developed basic technical specifications to be used in bidding for the phase 1 projects. It highlights the need for capacity building in the outer island utility FENAKA to support the pilot projects and future phases.

The renewable energy resource analysis supporting the proposed project is thin and contains no discussion on how the renewable energy share estimates were calculated. The solar PV resource is listed as 'unlimited' showing that insufficient analysis was undertaken. The data given only cover irradiance across large regions. Some data on seasonal variations are provided. It should be confirmed that the ADB study included a more detailed analysis that clearly demonstrates the viability of renewable energy projects envisaged.

Optimisation of diesel generation

The report draws attention to consistently oversized diesel generators causing low loading and inefficiency: "average diesel consumption in excess of 0.42 litres/kWh is relatively high. While the optimal level of operation that should yield 0.22-0.25 litres/kWh may not be achievable, an average specific fuel consumption rate of 0.35 litres/kWh is considered acceptable in the Maldives" (ADB, 2014).

The following recommendations are offered: "in the short term, these improvements could come through introduction of automatic controllers for generation to optimize allocation of generation across multiple gen sets, in addition to energy efficiency measures. In the longer term, there should be a proper planning approach adopted to determine size the generators to meet forecast load growth, as well as optimising across other generation (including solar PV) and demand-side resources" (ADB, 2014).

The report points out inefficiencies resulting from the lack of modern control systems. It also notes: "moreover, there is no central repository for the recorded data. The information is dispersed and not readily available" (ADB, 2014). The lack of data on diesel generator operations is a significant barrier to hybrid system deployment because an efficient design requires a clear understanding of how renewable energy generation will effect diesel operation. Efficient diesel generators are a key component of a cost-effective hybrid power system that includes a high share of renewable energy. All the issues identified above will need to be resolved before the hybridisation of these systems with solar PV and battery storage can be effectively undertaken. This may mean replacing older or oversized generators, which would increase the initial capital cost of the hybrid systems, but would pay back rapidly through substantial fuel savings.

Barriers to renewable energy investment

The ADB study identifies several barriers to investments in renewable energy. It notes that private sector development of renewable energy in the Maldives is constrained by investment perceptions, a nascent regulatory structure and inadequate public sector infrastructure to suitably integrate private sector renewable energy. The report also discusses how the lack of clarity in how environmental regulations impact renewable energy projects, noting that it is unclear whether or not an environmental impact assessment is required for PV systems**.** Moving beyond the five pilot projects identified for 2015 will probably require the resolution of policy and regulatory issues relating to renewable energy deployment to reduce risk and attract private investment.

The report highlights the specific roles defined in the Maldives National Energy Policy for the renewable energy transition for policy makers, regulators and utilities. It also gives details of specific renewable energy/electricity sector goals in the Maldives National Energy Policy. These insights can serve as a basis for examining policies and regulations that need to be updated.

Previous direct support

The report indicates that the World Bank has provided Maldives with support in developing its energy sector regulatory framework while ADB has provided support on capacity building on grid codes and tariff mechanisms. Other areas of support include power purchase agreement templates, site identification for private investment, business structure modelling including bundling outer islands to improve economies of scale and provision of risk guarantees to the private sector. The government should identify the key areas in which it requires additional support from development partners to continue improving the enabling environment and the local renewable energy deployment capacity.

SOLAR PV INTEGRATION IN THE MALDIVES

This ADB study contains analysis of various power electronics and grid operation strategies (referred to as 'smart grid options'). It considers how these can be used to improve diesel generator performance and maximise solar PV deployment in the Maldives without compromising the economic or technical performance of electricity grids. The study aims to answer the following questions clearly:

1) What is the maximum solar level (without storage) that can be supported without compromising economics and system security?
2) What diesel savings arise from solar generation?

The study divides the islands of the Maldives into four categories and attempts to develop solutions that would be broadly applicable across all the islands in each category. These categories are based on the size of the local power generation system and other considerations as defined below:

Small islands (typically <100 kW total peak load): potential candidates: K. Gulhi, K. Dhiffushi, K. Thulushdhoo, K. Naifaru, B. Goidhoo, Ha. Filladhoo

Resorts (typically 300-800 kW total peak load): potential candidates: Edmudu, Medhufushi, Huvarenfushi

Medium/large islands (significantly above 100 kW total peak load): potential candidates: Thinadhoo, Villingili, Thilafushi, K. Mafushi

Malé: The main island of the Greater Malé region with ca. 40 MW peak load.

For each category the study examines how a range of technical options including control systems, new generation assets, load management, energy efficiency and storage could be used to support increased PV deployment. This analysis seeks to determine an optimal configuration of the above technical options to define an economically optimal PV deployment strategy that does not affect system stability.

As an example, the study cites the need to address low fuel efficiency on many islands where fuel consumption can exceed 0.40 litres/kWh. Indeed, the study indicates substantial fuel savings can be achieved from optimising the operation of existing diesel generators, specifically it notes that for the medium/large island category, around half the potential fuel savings come from better diesel operation through system optimisation of hardware and software.

The ADB analysis covered 2013-2022 and used a representative island for each of the four categories to "calculate the benefit of improved planning/dispatch and load management practices supported through smart controls as well as solar PV as part of an optimised mix of supply and demand side resources." The study provides in-depth results giving specific technology deployment options for each island category. However, the study established that there is substantial opportunity for PV deployment in all four categories that does not threaten system stability or economic performance. At the top level the analysis showed that optimal PV deployment for the four categories would support the following levels of annual PV generation: small islands: 10%, medium/large islands: 12-32%, resort islands: 30%, Greater Malé: less than 10%.

The study states that economically and technically optimal PV deployment requires changes to the current regulatory structure. It notes that the present feed-in-tariff is too simple and does not reflect the complexities of deploying and operating PV systems. As an alternative, the study recommends examining net-metering. It also indicates that changes to the tariff structure will be needed to support PV deployment and suggests a full review of tariff policy is needed. It proposes the introduction of a time-of-use tariff to encourage load shifting from the evening peak, and interruptible load contracts for customers with larger deferrable loads. The study also notes "the need to have a clear policy driver such as some form of renewable energy target/quota/standard that would guide and accelerate the uptake of solar/renewable energy in Maldives."

It also indicates a need to enforce technical standards. It specifically calls for basic controller functions to be made mandatory. It says that with increased PV deployment, basic controller functions such as automatic start-up/shut down, load sharing and automatic recovery should be considered mandatory for all PV systems. It also recommends active demand-side management for air conditioning, water pumps, ice-making and other deferrable loads.

The study specifically cites the need for improved data collection and availability and recommends the following additional research to support PV deployment:

1) Electricity planning analysis to work out the appropriate generation and demand-side measures to support sustainable PV deployment.
2) Power system studies on solar integration that address the variability in the solar resource.
3) A renewable energy policy study that clearly establishes aggressive but achievable renewable energy targets based on economically optimal renewable energy system configurations.
4) A tariff design study that will prompt the creation of a tariff structure that can sustain PV deployment in the long term.

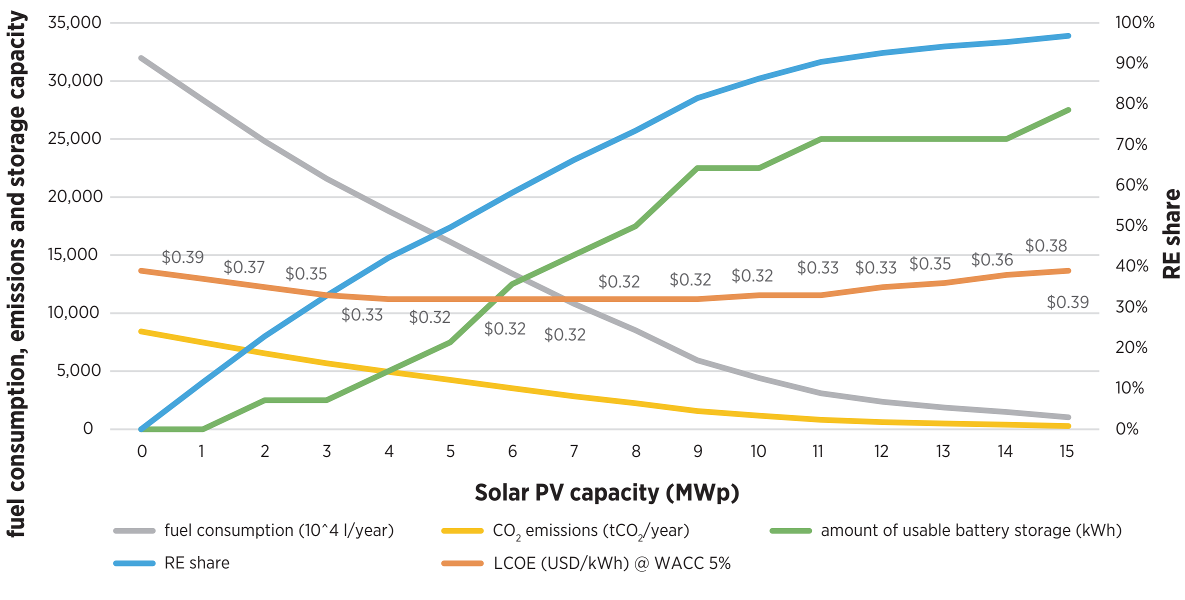
DEVELOPING AMBITIOUS BUT ACHIEVABLE RENEWABLE ENERGY TARGETS

The IRENA review of all the studies discussed above did not identify any substantive analysis to support setting renewable energy targets. The origins of the previous carbon neutrality goal and the current target for 30% peak electricity demand from renewable energy are not clear. The national carbon neutrality target may be technically achievable but the cost is likely to be economically prohibitive for some time. The goal of 30% of peak electricity demand for renewable energy is probably well below the economically optimal renewable energy deployment in the Maldives.

The government should thus strongly consider new renewable energy targets that will help accelerate the Maldives' transition towards renewables. These targets need to be based on modelling and analysis that confirms the targets are technically and economically achievable. In addition, policy makers and other stakeholders setting the renewable energy targets need to understand the interaction between renewables deployment and other key policy goals. Figure 2 shows results from the analysis of PV deployment in Villingili to demonstrate how raising renewable energy targets affects other policy goals. This analysis of PV deployment in Villingili is covered in detail in the annex to this report.

Figure 2 shows that increasing the renewable energy share has major impacts on key areas like the cost of electricity, the amount of fuel imports and greenhouse gas emissions. The assumptions used when analysing renewable energy targets have a very strong impact on the results. It is thus critical that these assumptions are as close to reality as possible. In addition, sensitivity

Figure 2: Impact of rising solar PV share in Villingili, Maldives



analysis should be included to determine the impact of key parameters. For the outputs shown in figure 2 the following assumptions were used:

- 5% weighted average cost of capital (WACC)
- minimum cost configuration for each additional MWp of capacity (except the last, in order to get as close as possible to 100% renewable energy share – 96.8% here)
- price of diesel (representative of Maldives) USD 1.02/litre
- USD 2 500/kWp installed for solar PV including grid-tie inverters
- storage is advanced lead-acid (OPzS), USD 1,200/kWh nominal, USD 1,714/kWh usable, system cost excludes battery charger and inverter
- battery charger and inverter for the storage system: USD 300/kW, size 1-5 MW
- real data have been used for load and generators in Villingili, Maldives. Annual peak load is around 2.25 MW. For a 2.25 MWp PV system with some storage, the annual PV generation reaches 25%.

CONCLUSIONS

IRENA analysis has shown that existing studies relating to renewable energy deployment in the Maldives provide the necessary information to support ambitious deployment of renewable energy in the Maldives. These studies identify viable renewable energy projects and provide solutions to the technical and policy barriers that will to need be overcome. However, it is critical that the government investigates the deployment of renewable energy options beyond those identified in studies reviewed. Defining clear, ambitious but achievable renewable energy targets based on an analysis of least-cost deployment pathways is central to this effort.

One area of concern relating to the deployment of renewable energy projects in the Maldives is the lack of consistency between the specific programmes and funding mechanisms detailed in the SREP Investment Plan and the projects described in most of the other studies that were reviewed. The lack of a clear connection between SREP funding and the projects identified in the other studies is a significant barrier to creating a low-risk environment for renewable energy investment, which is needed to attract the private financing envisioned in the SREP Investment Plan.

One of the key conclusions of the IRENA review is that the renewable energy deployment proposed in the various studies does not achieve the Maldives' full renewable energy potential. For example, the renewable energy potential from the *Greater Malé Region Renewable Energy Integration Plan* is well below what could be achieved in a least cost scenario. Using two different demand projections (business as usual and high growth) this study shows that installing the proposed maximum 43.5 MW of PV and wind potential in 2020 would only cover around 13-15% of annual demand in Greater Malé. The SREP Investment Plan envisions an even lower total renewable energy capacity of only 26 MW. The ADB report indicates that numerous islands outside the Greater Malé region can achieve a renewable energy share of 80% or more. Yet these islands do not represent a major proportion of national energy demand, which is concentrated in Greater Malé. Furthermore, approximately half the power generation capacity is owned by private resorts. It will be necessary to work with island resorts to reduce their diesel consumption by deploying renewable energy.

The government should consider setting ambitious but achievable renewable energy targets based on analysis that identifies economically optimal and technically feasible renewable energy deployment options. These targets should be clearly established in official policy documents and clearly communicated to drive the transition to renewable energy.

The government could consider a range of options to increase renewable energy deployment beyond the renewable energy generation options outlined in the studies reviewed. These options include:

- Policies and regulations to encourage PV deployment on private buildings. Existing studies restrict analysis of rooftop PV deployment to publicly owned buildings. However, the large majority of roof space in Greater Malé is privately owned. Encouraging private investment by residential and commercial customers could greatly increase PV deployment potential.
- Additional PV deployment options that bypass land availability constraints:
    - deployment of floating PV platforms based on successful Swimsol pilot projects
    - deployment of PV close to the shore on posts using the existing infrastructure employed to build water villas in many resorts in the Maldives
- deployment of around 80 MW of 'near outer island' wind power identified in the *Greater Malé Region Renewable Energy Integration Plan*
- use of energy storage, flexible generation and other measures outlined in this report to support integration of large shares of variable renewable energy (*i.e.* wind and PV)
- imports of sustainable solid or liquid biomass to cover the generation share that cannot be met by PV and wind generation due to land constraints
- energy efficiency programmes or non-electric renewable energy technologies such as solar water heaters and SWAC to reduce total electricity demand

TECHNICAL ANNEX: HOMER SIMULATIONS

To support the Maldives renewable energy roadmap, IRENA has conducted an analysis of the power systems on the islands of Gdh. Thinadhoo and Villingili using HOMER Energy simulation software. The goal of this analysis is to provide insights into the potential options for deploying PV in the Maldives. The analysis also seeks to determine whether the existing fuel-saver PV system installed on Thinadhoo can serve as a replicable model for PV deployment on other Maldives islands.

Thinadhoo model: replication of solar PV fuel-saver system

The Government of Maldives asked IRENA to review their Power System Expansion Plan for Gdh. Thinadhoo up to 2025. This plan examines the fuel-saver PV system designed to integrate a large share of solar PV without storage in Thinadhoo. The government wanted IRENA to assess its replicability to other islands with a similar electricity supply system size and structure. IRENA has established that the fuel-saver system can supply about 12.3% of the island's annual electricity generation. It uses a PV system with nominal capacity of around 50-60% of peak demand and no battery storage.

The fuel-saver system could provide a replicable model for the initial deployment of renewable energy on other islands. This is because it is a simple system that requires no battery storage and will probably not effect grid stability. The PV generation will simply be viewed by the existing power system as reduced electricity demand. However, the level of detail provided in the expansion plan is not sufficient to reliably establish the fuel-saver system's actual performance. Before this system can be considered for widespread replication, better analysis is needed that firmly establishes the actual impact on fuel consumption and the cost of generation. This analysis should also examine battery storage as this may provide a more cost-effective solution, allowing additional deployment of solar PV to displace considerably more diesel.

The following section contains the full results of the IRENA review of the expansion plan as well as a HOMER analysis examining the fuel-saver systems.

Definition of PV penetration

In the analysis conducted in the expansion plan, PV penetration is calculated as the ratio between PV capacity and diesel capacity. From a grid integration perspective, a more useful definition is the ratio of maximum PV generation over peak daily load, or better the maximum instantaneous share of PV in the system. This more widely accepted metric can provide indications of the possible impacts of PV in the system in terms of stability.

From an economic and policy perspective, the most useful indicator of PV penetration should be the ratio between annual PV production and total electricity demand. This metric allows the calculation of savings and progress in achieving renewable energy targets. This is because renewable energy policy targets are normally defined as the share of total electricity production and not instantaneous penetration. The metric differs from the previous ones in that it gives the percentage of kWh (energy) rather than the percentage of kW (power) being provided by the PV system. The analysis conducted in shows that when batteries are excluded the lowest levelised cost of energy (LCOE) is experienced at a PV penetration of approximately 15%. Where a battery is included the minimum LCOE is experienced at a PV penetration of around 50%.

Present power system

Thinadhoo currently has a power system based on the diesel and PV generation assets defined in table 5. The expansion plan was published in May 2014 and indicated that as of 2013 300 kWp of PV had been installed with another 250 kWp to be installed in the near future as part of the fuel-saver system. The IRENA analysis assumes the full 550 kWp of PV has been installed.

Table 5: Thinadhoo power system

Generation asset	Model	Capacity (kW)	Total capacity (kW)
Diesel generator	Cummins KTA38-G2	600	2 898
Diesel generator	Cummins KTA38-G3	728	
Diesel generator	Cummins KTA50-G3	1 020	
PV system		300	
PV system		250	

Figures 3 and 4 illustrate the fuel efficiency curves for the Cummins KTA38-G3 and KTA50-G3 diesel generators. These values were taken from the manufacturer's specifications and used to support IRENA analysis of the Thinadhoo power system. The fuel efficiency curve for the Cummins KTA38-G2 generator was not available so it was assumed to be the same as the fuel efficiency curve for the KTA38-G3 generator shown in figure 3.

Electricity demand

Using the demand date provided in the expansion plan, IRENA estimated electricity demand curves for a typical weekday and weekend day for use in the HOMER analysis. These demand curves are given in figure 5.

The expansion plan only provides electricity demand data for one week in July 2013 and no information on the seasonal variability in demand is provided. The IRENA analysis has thus assumed that the demand curves given in figure 5 do not change throughout the year.

Fuel-saver performance

Using the data on the existing power system and electricity demand given in the expansion plan, IRENA performed a HOMER analysis to estimate the fuel-saver system's performance. The results of this analysis provide some insights into the fuel-saver system potential to increase renewable energy generation.

Figure 3: Cummins KTA38-G3 diesel generator fuel efficiency curve

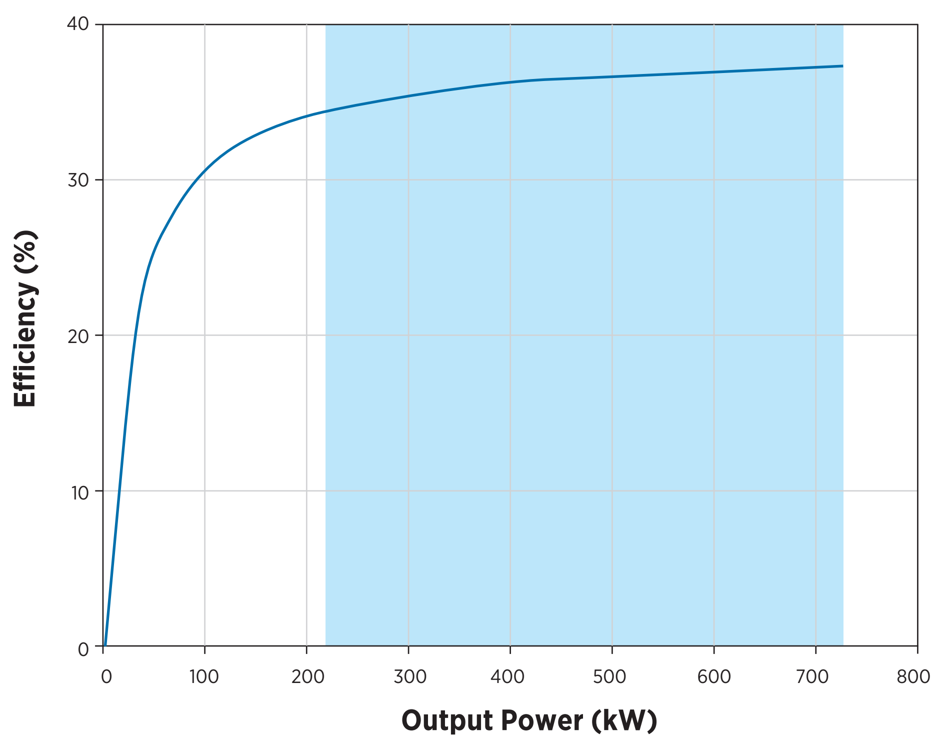


Figure 4: Cummins KTA50-G3 diesel generator fuel efficiency curve

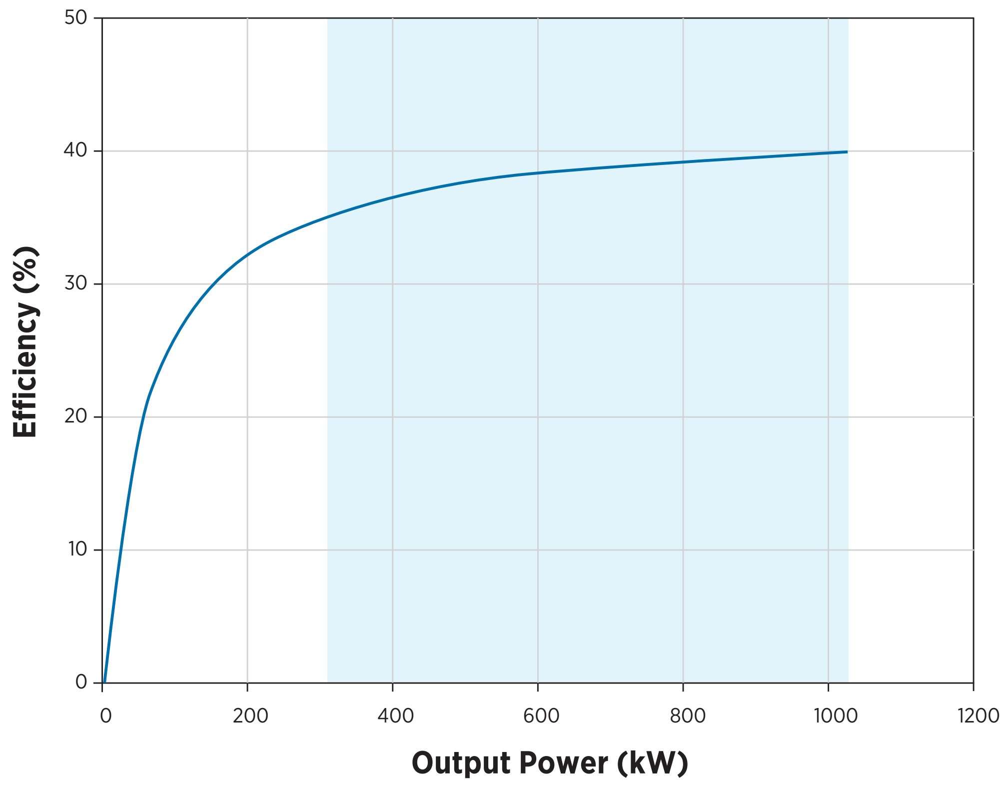


Figure 5: Comparison between average weekday and weekend load

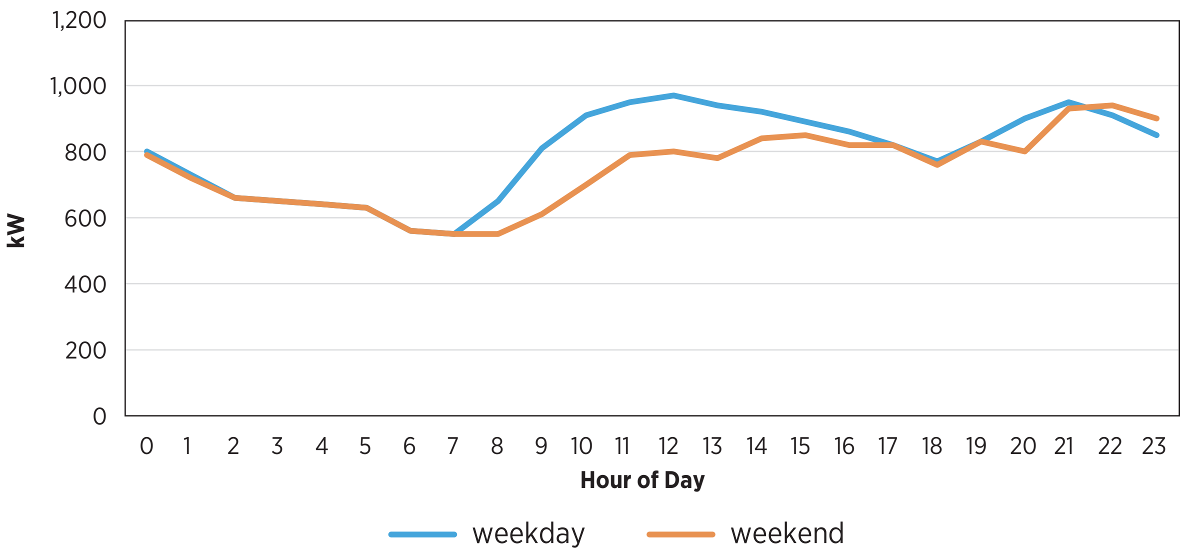


Table 6: IRENA HOMER analysis results: annual generation

Generation Asset	Capacity (kW)	Generation (million kWh per year)	Share
Cummins KTA 50 G3	1 020	3.91	57.1%
Cummins KTA 38 G3	728	1.31	19.2%
Cummins KTA 38 G2	600	0.78	11.5%
PV system	550	0.84	12.3%
Total	2 898	6.85	100%

However, the lack of sufficient data prevents a more accurate analysis that would confirm the estimated fuel saving. Furthermore, actual performance data are necessary to confirm efficient dispatching and real system performance.

Table 6 shows the generation share of each generation asset obtained from the IRENA HOMER analysis, which indicates that the 550 kWp PV system can cover approximately 12.3% of Thinadhoo's annual electricity demand. The expansion plan did not contain any data on the actual annual electricity demand in Thinadhoo. For a more accurate estimate of the fuel-saver PV share, the estimated PV generation of 839,720 kWh per year should be compared to Thinadhoo's actual electricity demand. However, these results make it clear that the 550 kWp system should be able to provide a significant share of Thinadhoo's electricity demand.

The fuel-saver system also has the potential to reduce LCOE in Thinadhoo. Figure 6 compares the LCOE of a system excluding PV and using only the island's diesel generators to the LCOE of the fuel-saver system that includes the 550 kWp PV installation. It compares the fuel-saver impact on LCOE for two different diesel prices. The expansion plan assumed oil prices would continue to increase to over USD 100 per barrel giving a diesel fuel cost of around USD 1.4 per litre on Thinadhoo in 2014. IRENA also estimated the reduction in LCOE at a diesel fuel cost of around USD 0.7 per litre, which corresponds to a more accurate oil price of USD 56 per barrel.

Figure 6 clearly shows the fuel-saver has the potential to reduce LCOE, giving a USD 0.025/kWh reduction with diesel at USD 0.7 per litre (9.2%) and a USD 0.047/kWh reduction with diesel at 1.4 USD per litre (10.1%).

Figure 6: Impact of fuel-saver PV on LCOE

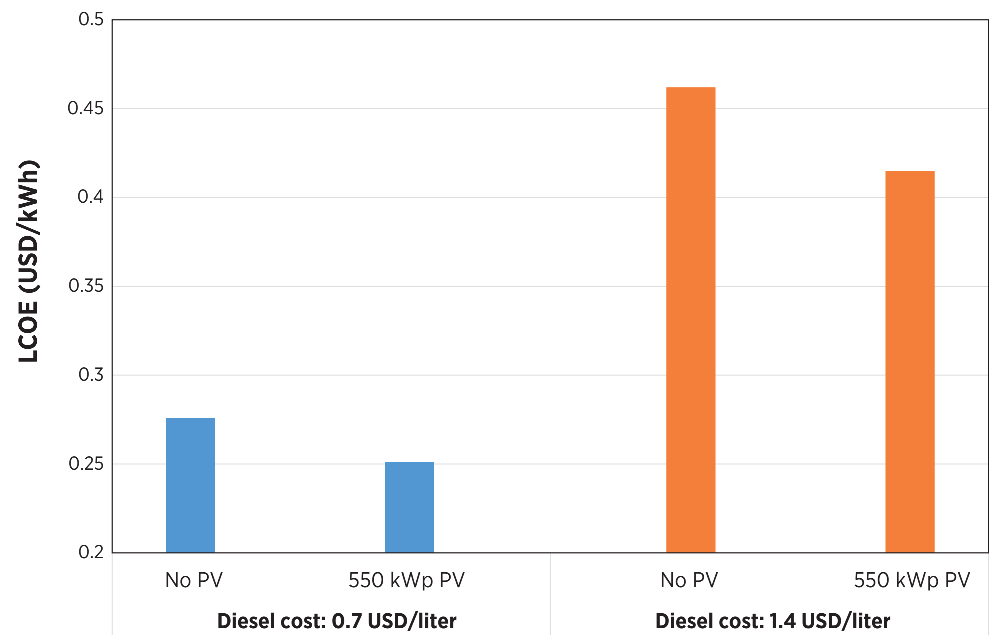


Table 7: Diesel generator operation comparison

Generation asset	Expansion plan numbering	Generator capacity (kW)	Operating hours per year	
			Current system	HOMER-optimised
Cummins KTA 50 G3	No.2	1,020	4,827	5,200
Cummins KTA 38 G3	No.3	728	2,897	2,445
Cummins KTA 38 G2	No.4	600	2,964	1,628
Total		2,348	10,688	9,273

Optimising diesel generator operation

IRENA analysis indicates a potential for fuel savings by optimising the operation of the diesel generators already installed on Thinadhoo. Table 7 compares the current diesel operation given in the expansion plan and the optimised diesel operation identified in the IRENA HOMER analysis.

As can be seen in table 7, the HOMER-optimised diesel operation relies more heavily on the KTA 50 G3 generator, which is more efficient than the KTA 38 G2 or G3 (see figures 3 and 4 for generator efficiency). The lack of data on diesel operation in the expansion plan limits the ability to make an in-depth comparison (only operating hours are given). This is also complicated by the fact that the report uses a numbering scheme for the generators, shown in table 7 as 'Expansion plan numbering' that does not clearly establish which generators are associated with the operating hours listed. However, the IRENA optimisation results indicate it is likely that the operation of diesel generators can be improved. This would increase fuel savings and lead to a more efficient operation of the fuel-saver

Figure 7: Homer-optimised operation of KTA 38 G2 generator

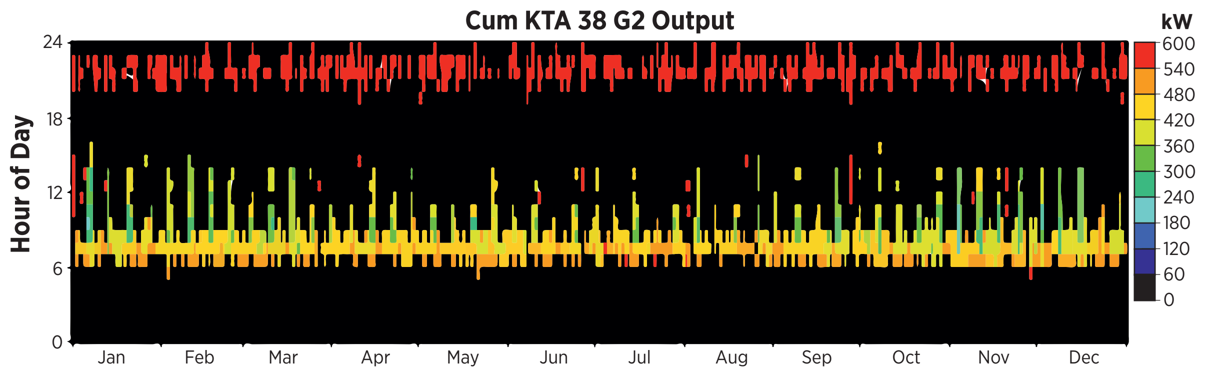


Figure 8: Homer-optimised operation of KTA 38 G3 generator

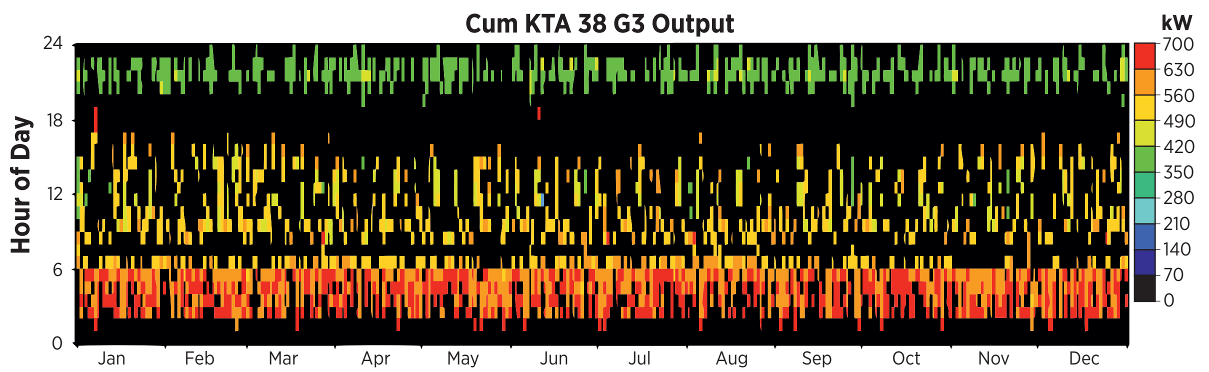
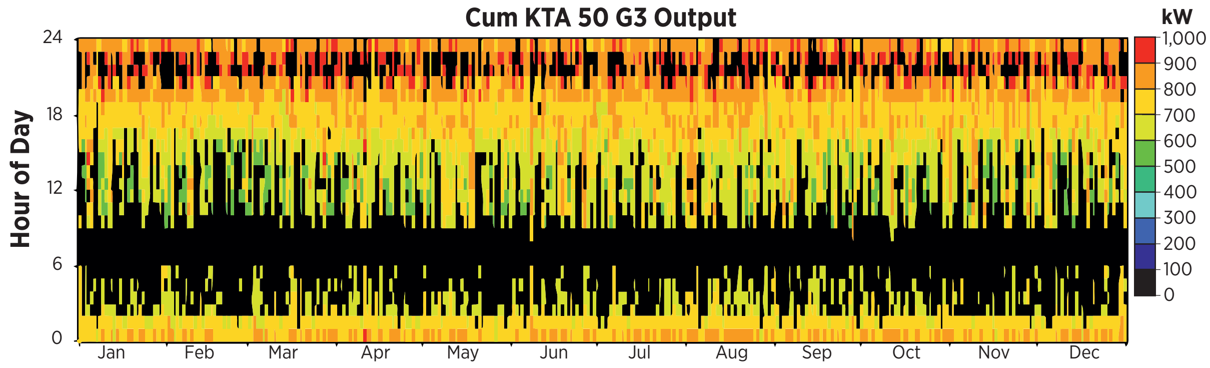


Figure 9: Homer-optimised operation of KTA 50 G3 generator



system. Figures 7, 8 and 9 provide a detailed view of the HOMER-optimised operation of the diesel generators in the fuel-saver system. Making a detailed comparison with actual generation data from Thinadhoo would be useful and would help optimise the operation of these units.

Additional data and analysis required

IRENA analysis indicates the fuel-saver system does provide a low-cost option for reducing diesel fuel consumption. However, to produce a replicable model for other islands in the Maldives, more data are needed on the system performance. Actual demand data for at least one year are needed to cover seasonal effects, total demand, minimum and maximum demand and other key factors. Actual generation data for at least one year for the diesel generators and PV system are needed to determine whether the system is being operated efficiently and establish the real fuel savings potential. In addition, the analysis should include the option of deploying battery storage as this can often lead to a more cost-effective system. The impacts of battery storage, the cost of capital and other key factors that would help improve the analysis of the Thinadhoo fuel-saver model are covered in detail in the following section. This outlines the IRENA HOMER analysis of PV deployment options for Villingili.

IRENA power system optimisation analysis for Villingili

To assist in determining which renewable energy options will support renewable energy in the Maldives, IRENA has carried out a quantitative analysis using HOMER software. This estimates the potential to deploy PV generation on Villingili. It assumes that PV will be integrated into the existing diesel-based power system to create a PV diesel hybrid system. The HOMER model used 2013 demand data including daily and seasonal demand variability and diesel generator information provided by STELCO. This was combined with publicly available sources to establish the economically optimal deployment of PV. This model also assessed the power generation costs of different system configurations to help fulfil the official 2010 Energy Policy goals to provide sustainable energy services at the lowest possible cost. This analysis can be replicated for other islands in the scope of IRENA work so long as a minimum amount of necessary data is provided by the government as per the commitment endorsed in the SoW.

Present power system

Villingili's power system consists of four diesel generators with a total combined capacity of 2,800 kW. Details of the power system are given in table 8. Based on the fuel efficiency curves in figures 10 and 11, it is expected that the larger KTA 50 G3 generators would be operating most of the time, alternating between the two to allow for maintenance and uniform ageing of the generation assets. The KTA 19 G4 generators are likely to be used only to serve peak demand or in high season, probably running a limited number of hours compared to the KTA 50 G3 generators due to lower efficiency. The model suggests an optimal dispatching strategy, which is likely to reduce fuel consumption at no cost if implemented.

Table 8: Villingili diesel generator characteristics

Engine type	Engine model	Operating Since	Capacity (kW)	Total capacity (kW)
Cummins	KTA 19 G4	31 May 2000	400	2,800
Cummins	KTA 19 G4	31 May 2000	400	
Cummins	KTA 50 G3	20 December 2004	1,000	
Cummins	KTA 50 G3	29 December 2007	1,000	

Figure 10: Fuel efficiency curves for Cummins KTA 50 G3 diesel generator

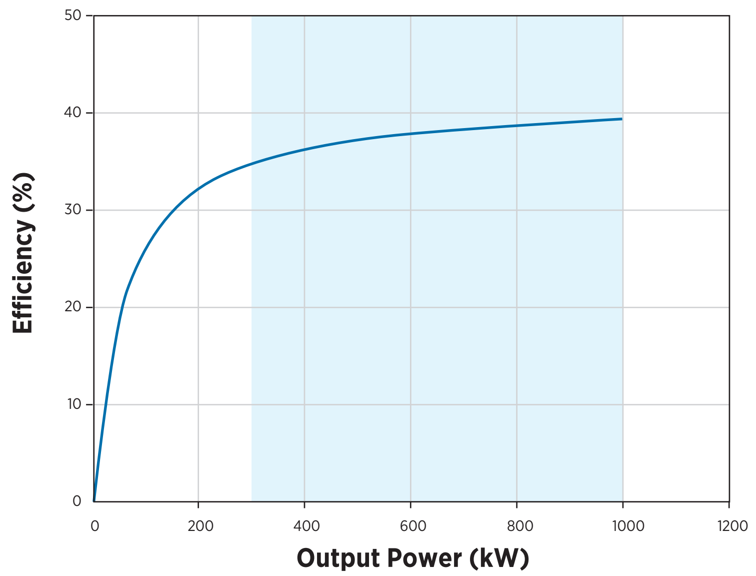


Figure 11: Fuel efficiency curves for Cummins KTA 19 G4 diesel generator

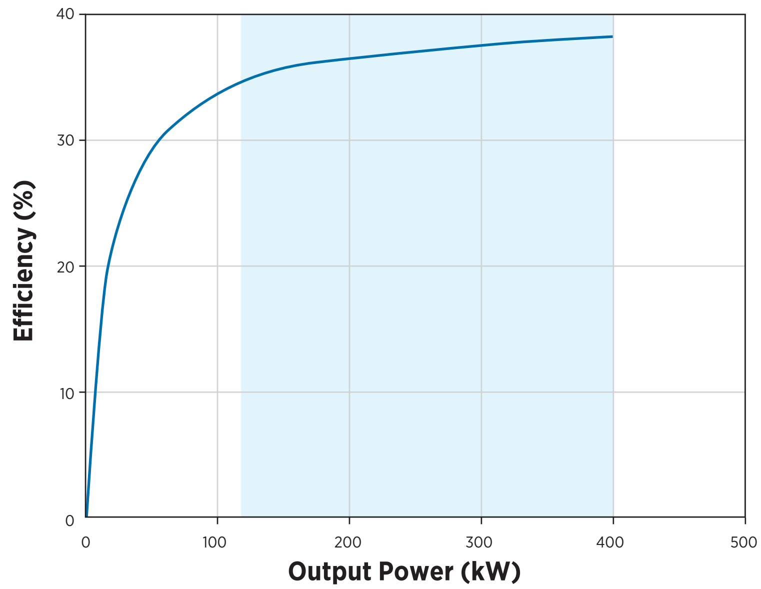
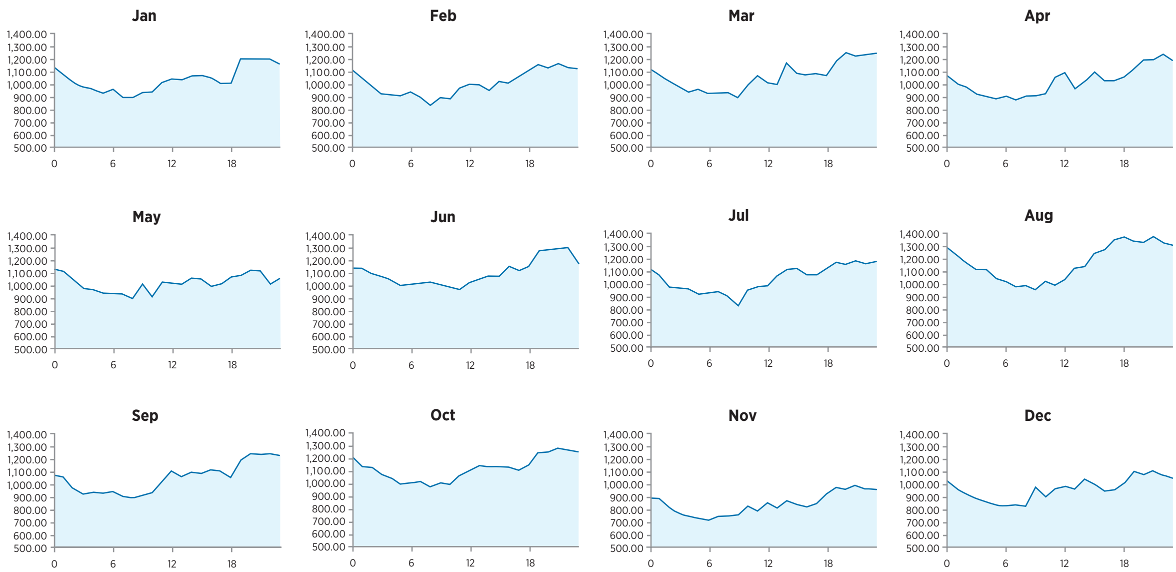


Figure 12: Daily electricity demand profile for a weekday in January 2013



Electricity demand structure and forecast growth

The demand data provided by STELCO covered one weekday and one weekend day per month for each month in 2013. The full hourly demand curve for 2013 has been estimated by IRENA on the basis of these data. The estimated demand curve, shown in figure 12, is based on stochastic parameters of intra-day and inter-day variability. They accurately reproduce the maximum peak demand provided by STELCO as well as the daily load curve.

A complete data series with hourly data logged for 2013 would allow a more accurate analysis. In particular, it would capture possible anomalous days where peak demand might exceed the capacity of the KTA 50 G3 generator.

Based on the demand data provided, figure 13 shows some seasonal variability with increased activity during summer and reduced activity in winter. The absence of data on the disaggregation of demand makes it difficult to understand whether seasonal variability is linked to tourism or different cooling demand due to weather patterns. As a result, the IRENA analysis assumed the following:

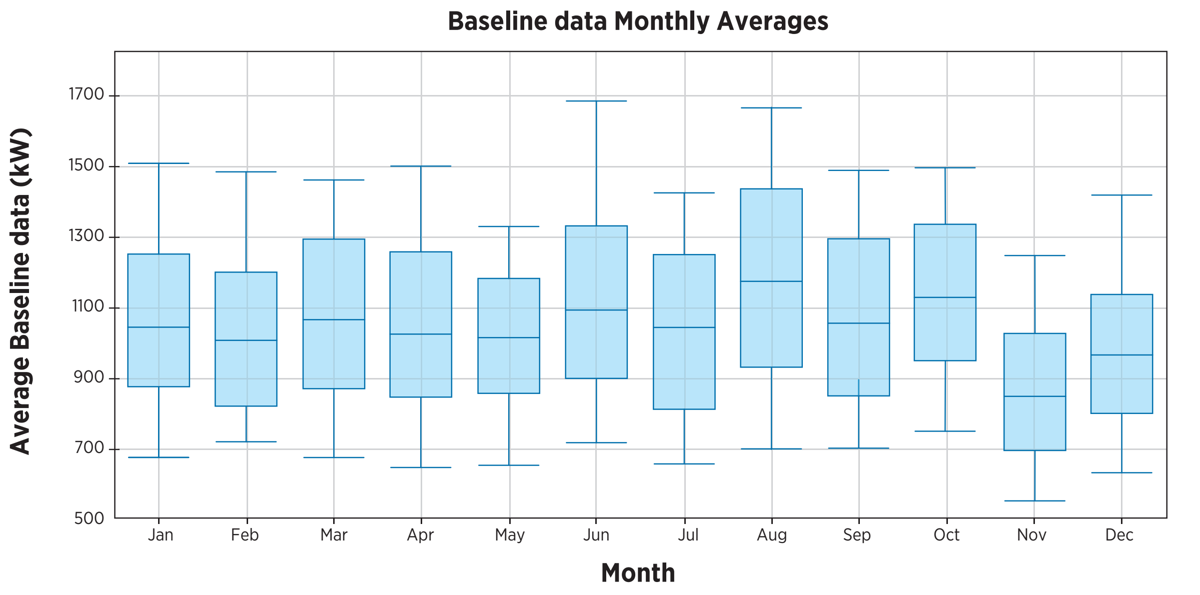
1) The shape of Villingili's seasonal load curve does not change over the period covered by the analysis.
2) The absolute load level grows proportionately based on the peak demand growth forecast provided by STELCO and illustrated in figure 14.

Based on the STELCO forecast, peak demand on Villingili is estimated to reach 2.5 MW in 2020 – around 30% more than in 2013. The diesel generator capacity (2.8 MW) already installed is sufficient to meet this estimated demand increase through the time frame of this analysis. Deploying renewable energy technologies would further delay the need for additional diesel capacity. It would cover part of the island's electricity demand and reduce the number of running hours for some generators, extending their useful lifetime.

Optimal power system

Due to the high cost of power generation from diesel and the declining prices of PV modules, PV is already cost-competitive with diesel-based power generation in the Maldives. As a result, integrating PV into the power system will cut generation costs. However, the maximum amount of PV that can be deployed on each island is limited by the following factors:

Figure 13: Seasonal electricity demand profile for Villingili



a) land availability
b) grid stability (for PV without storage)
c) cost-competitiveness of PV with increasing amounts of battery storage

PV is nominally cheaper than diesel-based generation. However, increasing the share of PV in annual electricity production while maintaining reliable grid operations will eventually require energy storage, which increases the generation cost of the system. Energy storage usually in the form of batteries is initially employed to support frequency because voltage can be supported by advanced inverters without the need for batteries. Once frequency stability concerns are addressed, additional storage may be necessary to cover temporary reduction in PV output resulting from cloud cover. Finally, a large increase in storage capacity would be necessary to serve night-time demand using electricity generated

Figure 14: Historical peak load and estimated growth

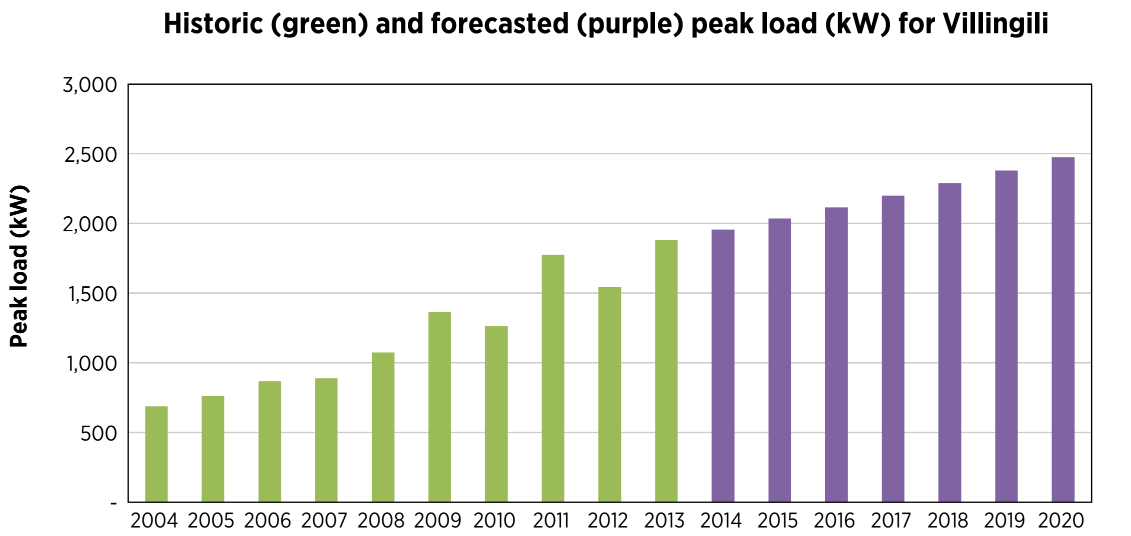
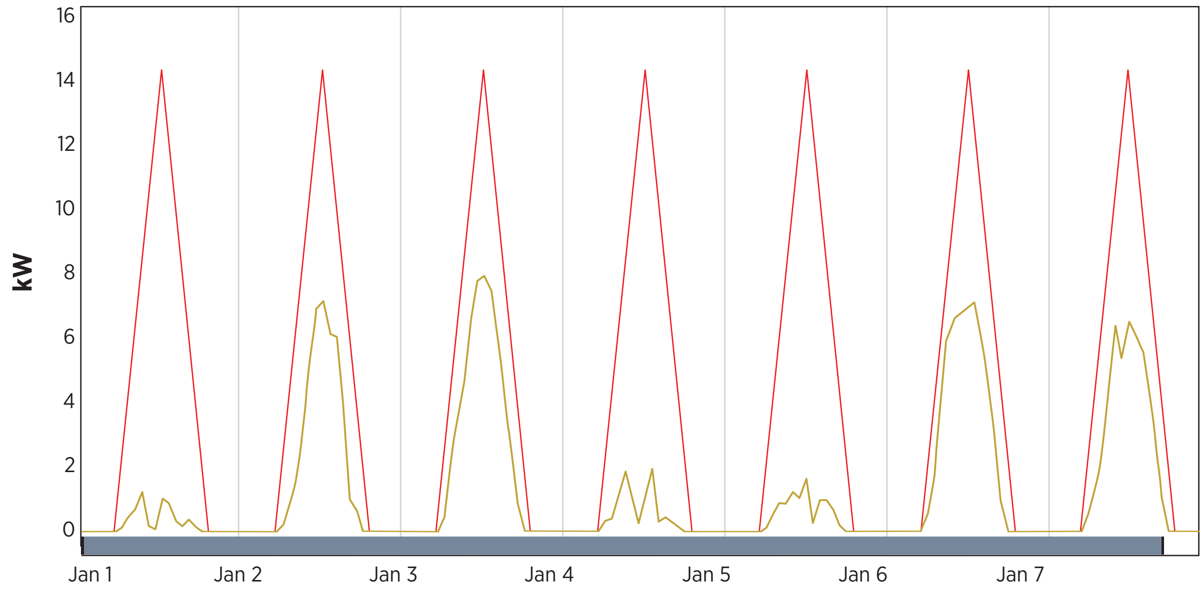


Figure 15: PV generation (yellow) with peaking electricity demand (red)



by PV during the day. The optimal amount of storage needs to be assessed on an island-by-island basis as it is highly dependent on individual factors. These include, for instance, load shape, cloud patterns, availability of deferrable loads (*e.g.* ice plants, thermal storage in cooling and refrigeration systems), cost of capital, PV price, battery price, fuel price.

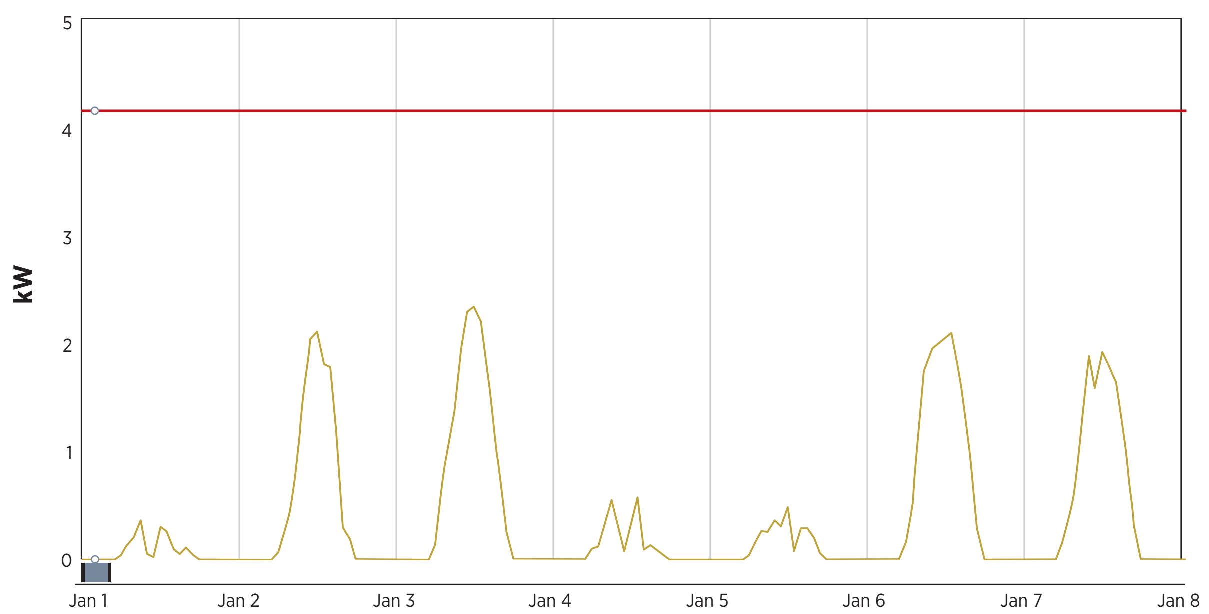
A generic example presented in figures 15 and 16 demonstrates the importance of load shape on the possible contribution of solar PV into a diesel grid in the absence of battery storage. This example is based on the model fuel-saver system developed in the expansion plan analysis for Gdh. Thinadoo, which allows a maximum ratio between solar PV capacity and peak load at 60%, which has been assumed as a constraint. Energy storage is necessary to release this constraint. In the absence of energy storage, and with current technologies, an instantaneous penetration of 60% in power as opposed to energy is a reasonable assumption. How this instantaneous penetration is translated into renewable energy share depends on load shape.

Figure 15 assumes that the load is essentially a theoretical and simplified air conditioning load for an office. Peak load is 14 kW and is assumed to happen at the same time as maximum production from solar PV, so maximum allowed PV size is 8.5 kWp. Based on Maldives solar radiation, the PV system can supply up to 30% of annual electricity demand in this configuration.

Figure 16 assumes the same daily electricity demand. However, the demand is distributed evenly during the day. This could be the case for an industrial load working 24 hours a day at a constant load. In this case, peak load goes down to around 4 kW with a maximum allowed PV size of around 2.5 kWp. In this configuration, a PV system in the same location as the previous example can only supply around 7% of annual electricity demand due to the smaller size allowed by the constraint on maximum instant penetration.

This generic example illustrates the influence of the load shape on the possible contribution of solar PV and the consequent cost of power generation for the Maldives. PV can produce electricity at a lower cost than diesel. This means the more PV that can be integrated without storage, the lower the average cost of generation. This general observation about the importance of matching load shape with PV production remains valid in the case of PV with battery storage although it is more complex to quantify. The amount of storage necessary to supply the same share of PV in figure 16 would be much higher (*e.g.* easily four times as much) than that necessary to supply the load in figure 15. In the most obvious case, a

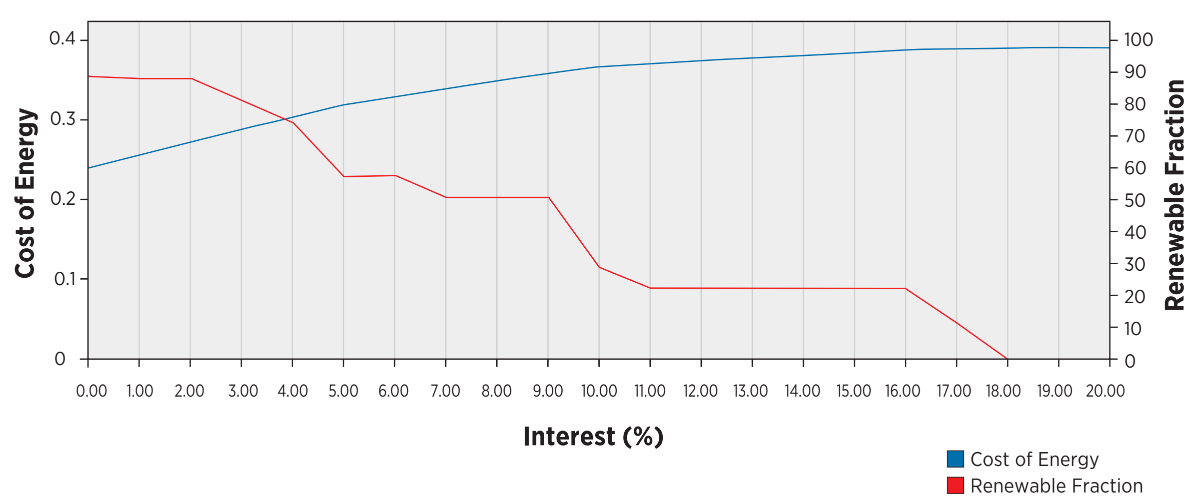
Figure 16: PV generation (yellow) with flat electricity demand (red)



substantial amount of energy storage would be required to integrate 8.5 kWp of solar PV in figure 16. Yet no storage is required to integrate the same amount of PV in figure 15 (fuel-saver system).

The cost of capital drives the optimal amount of energy storage and PV (*i.e.* the amount providing minimum cost of generation or maximum net present value for the renewable energy investment). Figure 17 shows how the amount of PV and batteries recommended for the same scenario changes dramatically when one alters just the cost of capital. The key reason for the correlation between the cost of capital and the ability of PV and battery storage to reduce generation costs is that PV generation cost is almost exclusively driven by upfront investment while diesel generator generation cost is mostly driven by fuel cost. This means access to affordable capital will be essential if PV is to reducing

Figure 17: Cost of energy and renewable energy share in the least-cost solution at different interest rates



system generation cost in the Maldives. Trying to reach the same objective with expensive capital would increase the cost of supplying electricity. Trying to minimise the cost of generation using expensive capital would limit or prohibit solar PV deployment. This would create a trade-off between renewable energy deployment and electricity affordability, both key objectives in the *Maldives National Energy Policy and Strategy*.

According to the SREP Investment Plan, the PV potential for Villingili is 1 MWp. Using this constraint, IRENA analysis shows that the amount of PV giving the minimum cost of power generation and maximising the net present value is the maximum allowed, 1 MWp. Due to possible concerns about grid stability, and in the absence of a grid assessment study confirming or dismissing these concerns, one battery bank has been included. This can compensate for anything up to a complete loss of PV generation for approximately six minutes. This battery would not be used to serve part of the peak load in the evening using electricity stored from PV but just to reduce possible concerns about grid reliability. This analysis does not void the need for a grid assessment study as part of the design of such a system.

Deploying 1 MWp of solar PV in Villingili would replace around 15% of electricity generated normally from diesel with renewable energy. Assuming a soft loan (2.5% WACC) to finance the PV project, the resulting cost of generating electricity would be USD 0.364/kWh. This would reduce the generation cost compared to present operations based exclusively on diesel, for which our analysis estimated a generation cost of USD 0.394/kWh. This assumes diesel generators are dispatched in a perfectly optimised manner.

Figure 18 shows a limited monthly contribution from PV (15% on average). However, an hourly chart for a full month shows that instantaneous penetration of solar PV often reaches a very high share, requiring energy storage to stabilise possible fluctuations in load and PV output. According to our analysis, as much as 4% of PV production could have to be curtailed due to excessive instantaneous penetration. However, this analysis is based on hourly estimated data. To be more accurate, higher frequency data would be necessary. Additional storage might make economic sense if more detailed analysis shows the need for a greater amounts of curtailed PV generation. A detailed operational assessment of the grid would provide more accurate results.

On the basis of the 2013 load profile, this analysis shows that deploying 1 MWp of solar PV in Villingili means renewable energy can contribute 15% of electricity. It also cuts power generation costs by around 10%. This assumes a WACC of 2.5% in line with the parameters of a soft loan.

Load increases would reduce the contribution of PV. As discussed above, if the load increases by one third in

Figure 18: Monthly contribution of PV to electricity production, 1 MWp array in Villingili

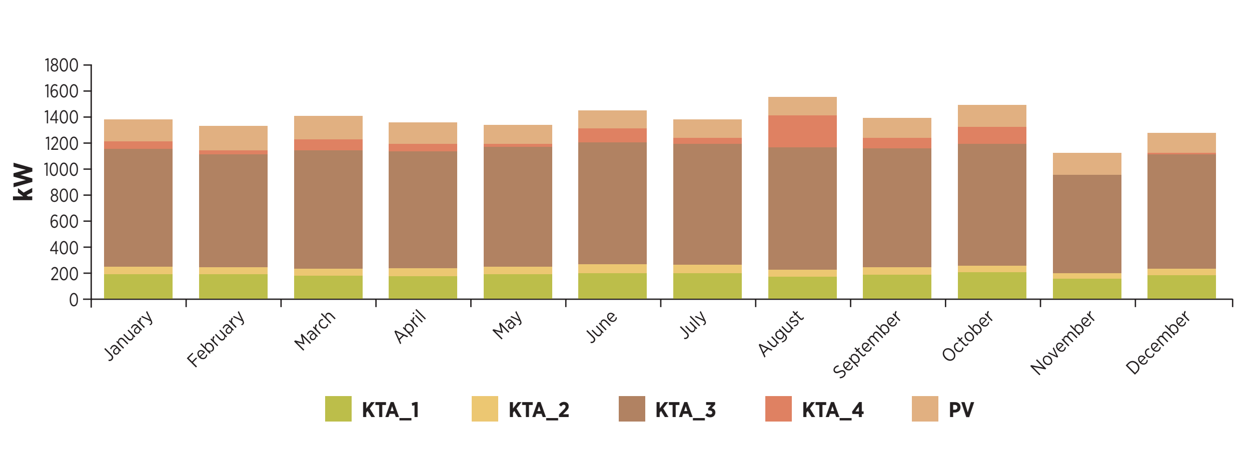
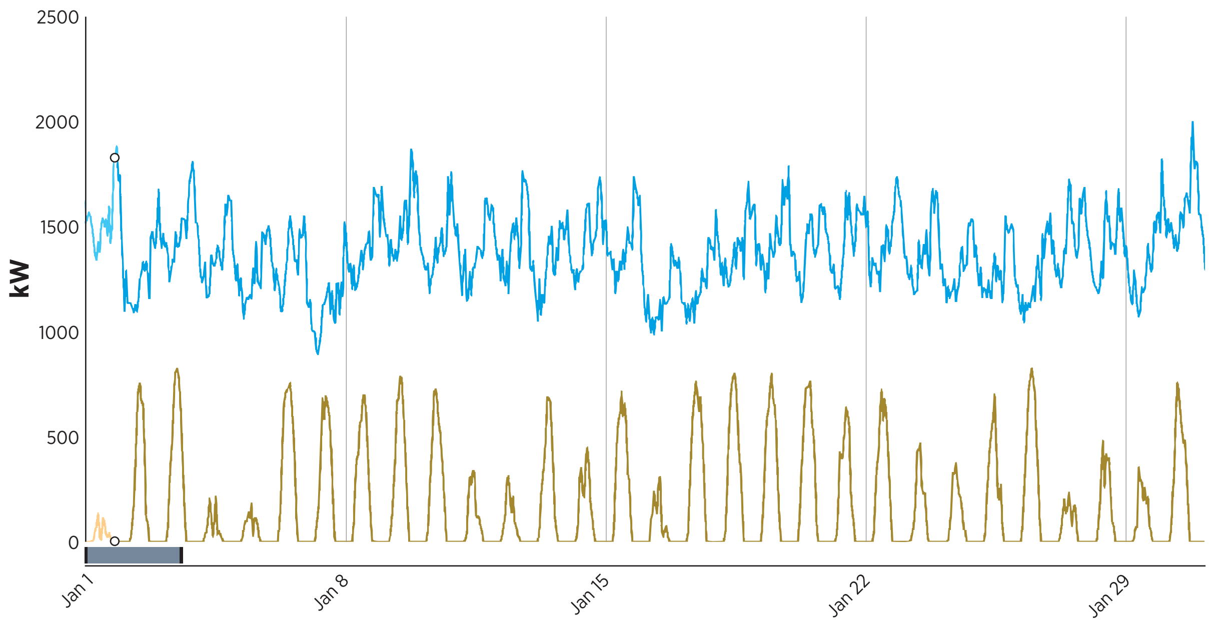


Figure 19: Hourly 1 MWp PV production (yellow) vs. total hourly electricity demand (blue)



2013-2020, PV contribution reduces to 12% assuming maximum potential is indeed 1 MWp. This 33% increase is based on the peak load increase estimated by STELCO without changing load shape or load distribution stochastic parameters.

Assuming no constraints on available space and system cost, the optimal system configuration to supply power to Villingili in 2020 includes 9 MWp of solar PV and 25 megawatt-hours of battery storage. This leads to a renewable energy share of 84% and a generation cost of USD 0.288/kWh assuming 2.5% WACC. This system would require more than 0.1 square kilometres of available land (around 40% of Villingili's land) and available capital for investing USD 32 million. The savings are guaranteed by a reduction in diesel consumption from an annual estimated 3.2 million litres to just 0.6 million litres. A detailed assessment of rooftop space, pole-mounted solar PV systems in shallow water and floating PV is necessary to define the actual limit to the PV capacity that can be installed in Villingili. Electrical interconnection would also allow PV installation in islands with more rooftop space (*e.g.* Malé) or a large lagoon area.

This analysis provides more information than the existing literature reviewed. It can be replicated for all Maldives islands so long as the minimum necessary dataset is supplied. However, the key messages on the elements relevant to identifying the optimal system for each island remain applicable to other islands too.

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