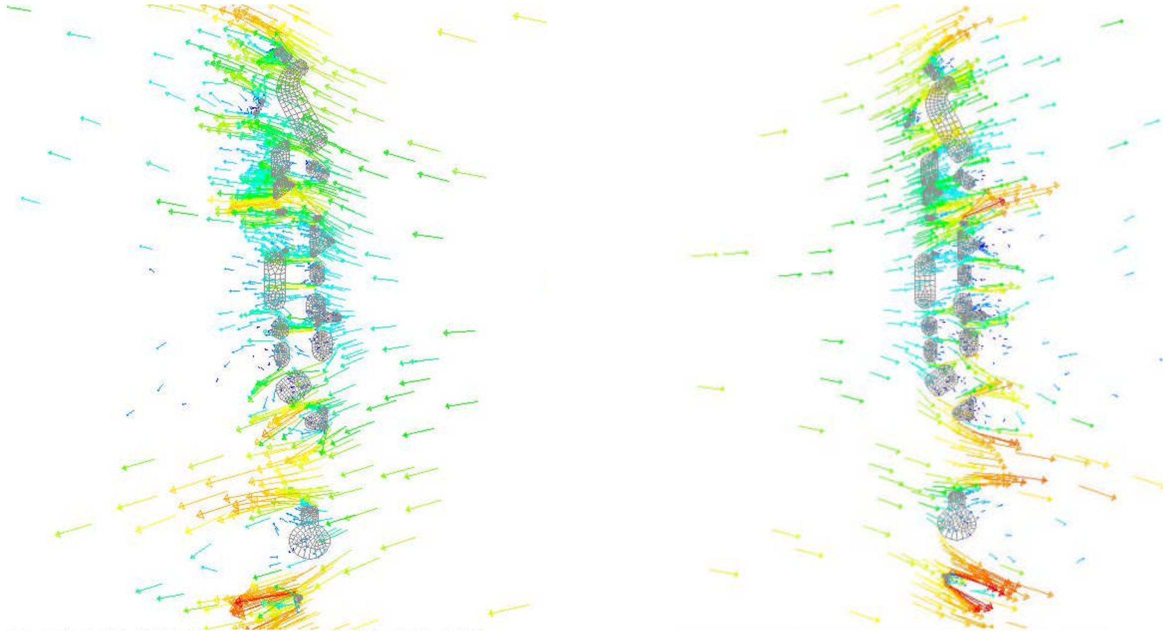
Marine Energy in the Maldives

Pre-feasibility report on Scottish Support for Maldives Marine Energy Implementation

Final Report – part 1 of 2: Main Report



Centre for Understanding Sustainable Practice
Robert Gordon University, Aberdeen, Scotland

Aberdeen, July 2011

Marine Energy in the Maldives
Pre-feasibility report on Scottish Support for Maldives Marine Energy Implementation

Final Report – part 1 of 2: Main Report
A separate report is available with background information and research findings
called 'Final Report – part 2 of 2: Annex Report'.

Images at the cover:
'Flow around the Maldives for the mean E-W and W-E open ocean current speeds' by CUSP, 2011.

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Executive Summary

This report looks into the potential of marine energy in the Maldives. The Government of the Maldives aims to be carbon neutral by 2020 whilst the Scottish Government aims to achieve a 42% reduction in emissions by 2020. To emphasize this common goal, they have signed a Joint Statement during the UN Climate Change conference that took place in Copenhagen during December 2009. The aim of the research and this report is to support the Government of the Maldives in their decision making process on implementing renewable energy, in particular marine energy. Based on initial discussions with those involved in the Maldives developing the future energy strategy for the president, it was decided to focus on Male' Atoll. The Scottish Government has funded the research that is underlying this report.

The team working on the study has longstanding experience with marine energy in the Maldives, Scotland and elsewhere. From the 4th till 14th of April, a research trip was made to the Maldives. Local data were collected and various stakeholders such as the Ministry of Environment, the State Electricity Company (STELCO), the Environmental Protection Agency, the Maldives Meteorological Services and numerous divers, boat captains and fishermen were interviewed. A boat was hired to conduct top-level current measurements of selected channels. Because of the timing of the study, this trip could only be made in April 2011. Unfortunately, April is the transition period between the north-eastern (winter) monsoon and the south-western (summer) monsoon and only shows the lightest currents. However, relatively swift current speeds were observed at a number of channels that were assessed, and based on the collected data, a preliminary indication of the potential of the local currents could still be made.

The resource assessment carried out indicates that the Maldives are likely to have a significant current resource however insufficient data were available to allow an accurate estimate of this resource to be made. The CUSP model of monsoonal current resource demonstrated that the flow around the Maldives is complex and, as such, it is not possible to judge which channels will have a large extractable current resource by considering their position on the atoll rim and their orientation. Results from the CUSP model also indicated that channels with a large extractable current resource for one monsoonal current direction typically had a much smaller extractable current resource when the monsoonal current was flowing in the opposite direction.

Conclusion The current installed capacity based on fossil fuel generation is sufficient to meet the current Maldivian needs. However, shortages are expected, in particular in the greater Male' capital area, and to deliver on the ambition to become carbon neutral in 2020, a very ambitious transition towards a renewable energy portfolio is needed to meet the future energy needs of the Maldives. Renewable energy sources such as solar and wind have their limitations, mainly due to their impact on the landscape and thus their potential impact on a reduced attractiveness of the tourism sector which forms a third of the Maldivian economy. Marine renewable energy has the distinct advantage of being very scalable, being well-suited to small mini-grid applications in remote communities, as well as larger scale installations for areas of high demand such as Male'. Furthermore, it is the only renewable energy option that can have no visual footprint. CUSP looked into two marine energy options for the Maldives: currents and ocean thermal. CUSP's research showed that it is likely that in the foreseeable future marine energy from currents will be part of the renewable energy portfolio in the Maldives, but that it is unlikely that ocean thermal energy will form part of that portfolio.

First recommendation **Further research in specific channels to define detailed marine resources** Selecting appropriate turbines for deployment in channels in the Maldives requires a detailed knowledge of the variation of flow speed at the sites over a longer period, ideally a year. A three phased-feasibility study is recommended to obtain independent in-depth current profiles as a further detailing of the current modelling done by CUSP. Until such time, it is advisable for the Government of the Maldives to remain technology agnostic. Partnering too early with specific technology providers could result in a scenario whereby the Government of the Maldives is obliged to use technology that is not suited to the particular channel and current characteristics, and will not deliver maximum energy at the most economical cost.

Second recommendation **An integrated energy approach** The implementation of marine energy facilities should be firmly grounded in an integrated energy strategy to fulfil future energy needs in the Maldives, establish a future-proof energy portfolio and to make the transition to a carbon neutral nation.

Third recommendation **Community & societal acceptation** Structural security and on-going care of the renewable energy facilities is reliant on the value placed on it by the community. Communities need to be involved in the implementation of renewables.

Fourth recommendation **Capacity building** Capacity building and skills transfer by foreign academic organisations and technology providers will lead to local job creation and improve the overall sustainability of the marine energy sector. The development of a successful marine energy sector would assist the Maldives in meeting their 2020 Carbon Neutral goal, whilst also bringing social and economic benefits.

The final report covering the findings of the pre-feasibility study on marine energy in the Maldives consists of two parts. Part 1 – this document – is the Main Report. This report provides a summary of the research findings on the locally available resources in the Maldives, the current state of marine technology and provides the main conclusions and recommendations. Part 2 is the Annex Report and consists of all the different research findings of the underlying research that formed the input for the Main Report.

Acknowledgements

This report contains the findings of a pre-feasibility study by Robert Gordon University into the potential of installing marine energy technologies in the Maldives. This study has been funded by the Scottish Government as by Offer of Grant on the 4th of February.

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1. Introduction

This report looks into the potential of marine energy in the Maldives. The Government of the Maldives aims to be carbon neutral by 2020 whilst the Scottish Government aims to achieve a 42% reduction in emissions by 2020. To emphasize this common goal, they have signed a Joint Statement during the UN Climate Change conference that took place in Copenhagen during December 2009.

The aim of the project is to support the Government of the Maldives in their decision making process on implementing renewable energy, in particular marine energy, in their attempt to become carbon neutral in 2020. Initial research performed by RGU had shown that sufficiently strong (>2.5 m/s) marine currents do exist though these are monsoonal (not tidal) and their location may not be the most convenient. Another part of the potential marine energy mix could be ocean thermal energy, using the thermal gradient between the shallow waters around the Maldivian atolls and the immediate drop into deep ocean water within short distance from the coast.

This report seeks to provide insight into the available marine resources in the Maldives and into the available technologies, to enable politicians and policy makers to make a deliberate decision whether to further investigate marine energy options in the Maldives.

By sponsoring the underlying research and writing of this report on marine energy in the Maldives, the Scottish Government as grant provider, delivered on its responsibility to share Scottish collective knowledge and expertise, in particular marine energy, on the international stage. This underlying pre-feasibility study was granted funding for 6 months on the 4th of February 2011. The study knew two main phases: an assessment of the available local resources in the Maldives, the current state of marine technology and the local context, and secondly, a synthesis of the assessment results leading to a conclusion about the potential of marine energy in the Maldives.

From the 4th till 14th of April, a research trip was made to the Maldives (Annex I of the Annex Report provides a detailed report of this trip). Local data were collected and various stakeholders such as the Ministry of Environment, the State Electricity Company (STELCO), the Environmental Protection Agency, the Maldives Meteorological Services and numerous divers, boat captains and fishermen were interviewed. A boat was hired to conduct top-level current measurements of selected channels. Because of the timing of the study, this trip could only be made in April. Unfortunately, April is the transition period between the north-eastern (winter) monsoon and the south-western (summer) monsoon and only shows the lightest currents. However, relatively swift current speeds were observed at a number of channels that were assessed, and based on the collected data, a preliminary indication of the potential of the local currents could still be made. Annex II provides the background on the currents modelling.

Based on initial discussions with those involved in the Maldives developing the future energy strategy for the president, it was decided to focus on Male' Atoll. These discussions revealed that the need for energy in Male' will rise from 45MW at the moment to 80MW in 2020. Since most of the rise in need will be around the capital Male', energy production capacity should be close to the capital. Plans are being developed for a sub-sea cable to link the capital and the adjacent islands: Viligili[1] to the west and Hulhule and Hulhumale' to the northeast.

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[1] Spelling of Maldivian names throughout this Main Report is according to the charts by the Hydrographic Office (1994).

The team working on the study has longstanding experience with marine energy in the Maldives, Scotland and elsewhere. The team has worked on marine energy potential in the Maldives since 2005. In 2009, president Nasheed announced his Carbon Neutral aspirations and spoke with our team member about taking the initial findings of marine potential in the Maldives further. At the UN Climate Change Conference in Copenhagen during December 2009, the Scottish Government signed a Joint Statement with the Government of the Maldives to develop and deepen the relationship between the two nations and to further cooperate in meeting the challenges and opportunities posed by climate change.

The final report covering the findings of the pre-feasibility study on marine energy in the Maldives consists of two parts. Part 1 – this document – is the Main Report. This report provides a summary of the research findings on the locally available resources in the Maldives and the current state of marine technology. Chapter 2 looks into current and ocean thermal energy conversion in the Maldives. Chapter 3 gives a broad overview of the local context for the implementation of marine energy, followed by the conclusions and recommendations in Chapter 4. Part 2 is the Annex Report and consists of all the different research findings of the underlying research that formed the input for the Chapters 2 and 3 and ultimately Chapter 4 of the Main Report.

2. Available marine resources and technologies in the Maldives

In the Maldives, there are potentially two sources of marine energy available: currents and ocean thermal. Both are described in more detail in this Chapter. The natural resources available as well as the marine technologies that are known today have been explored and described. The focus is on Male' Atoll, with the capital Male' and the three adjacent islands, Viligili to the west and Hulhule and Hulhumale' to the northeast.

2.1 Currents

2.1.1 Introduction

The Maldives is an area known for strong currents (Molteni, 2009). Current speeds in the deep channels between the atolls are typically in the range of 1-1.5 knots (0.51-0.77 m/s) (Hydrographic Office 1992, 1993a, 1993b, 1993c) however the current speeds in the channels through the rims of the atolls can be considerably higher, with speeds of 3.5-5.0 knots (1.5-2.6 m/s) reported for some of the E-W channels in the atolls (Hydrographic office 1994). The currents are caused by the interaction of oceanic currents, tidal currents and local wind induced currents. The speed of the resulting currents is determined by the relative speeds and directions of these different currents. Waves and the local bathymetry and topography can also have an effect on current speed and direction. Recently there has been a lot of interest in the extraction of energy from ocean currents. This section looks at the feasibility of extracting energy from currents in the Maldives. Further background information can be found in the Annex Report: Annex I. Report on fieldtrip to the Maldives, Annex II. Report on currents modelling, Annex III. Currents, Annex IV. TE overview and Annex V. TE Technology providers.

2.1.2 Overview of currents

The magnitude of the current resource of the Maldives can be estimated from individual estimates of the oceanic current, tidal current and local wind driven current resources and an understanding of how other factors can influence currents. Below, each type of current is considered in more detail.

Ocean currents

Ocean surface currents are driven by the wind (Trujillo and Thurman, 2011). In the Indian Ocean the seasonal wind pattern causes the ocean surface currents to switch direction. During the summer (May to September) the current flows from west to east and during the winter (November to February) the current flows from east to west. The transition between the two current systems occurs in March/April and October.

A variety of methods have been used to make measurements of surface current speeds in the Indian Ocean. Measurements have been made using various drifting objects, a fixed array of profiling current meters and satellites fitted with radar altimeters. Satellite data are available which give the variation of mean surface current speed over a period of approximately sixteen years in areas to the east and west of the central Maldives (See Annex III for detailed graphs.)

For the magnitude of the ocean current resource of the Maldives to be estimated, the speed of the currents in the channels in the atolls needs to be known. In order to relate the surface velocity of the monsoonal currents to the flow speed in individual channels in the atolls, a computational fluid dynamics (CFD) model of the Maldives has been developed by CUSP (See Annex II for details of modelling). The CUSP model is a two-dimensional model in which the atolls are represented by simplified shapes (Figure 1). The atolls are assumed to be porous, with their porosity determined by the ratio of channel to reef and island around the perimeter of the atoll.

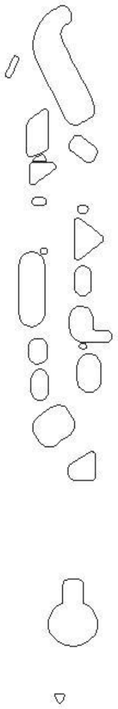


Figure 1- Simplified representation of atoll shapes used in the CUSP model.

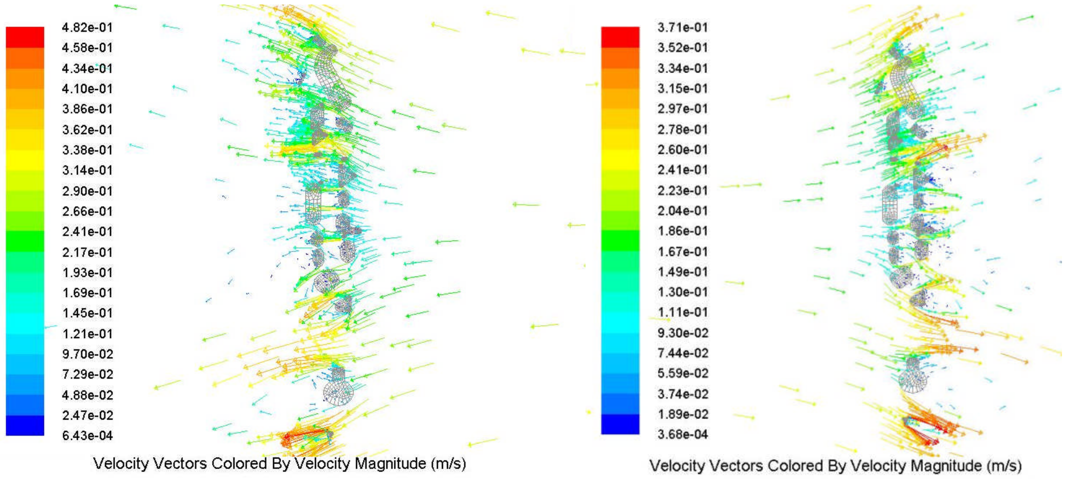
The CUSP model was run for the maximum, minimum and mean open ocean current speeds of the satellite data sets (NASA, 2011). The current speeds in a number of channels in Male' Atoll and South Male' Atoll were calculated from the results of the model. The positions of the channels for which current speeds were calculated are shown in Figure 2. A correction factor was applied to the calculated flow speeds in order to take into account the acceleration of the flow as it moves from the open ocean into the much shallower channels.

For each of the flow speeds that the CUSP model was run for, the power in the water passing through the cross section of each channel was calculated. There was a lot of variation in the amount of power passing through the different channels. These differences could not simply be explained by considering channel orientation and position. There was also a significant variation between the power passing through a channel when the flow was from east to west (E-W) and the power passing through the same channel when the flow was from west to east (W-E). These differences are because the presence of the Maldives significantly alters the flow from the uniform east-west or west-east currents.

Figure 3 shows the flow around the Maldives for the mean W-E and E-W open ocean current speeds. It can be seen from this figure that the flow diverges as it approaches the Maldives. This means that the direction of the flow depends on both the current direction and the position of the atoll in the island chain.

Figure 4 shows the flow around Male' and South Male' in more detail.

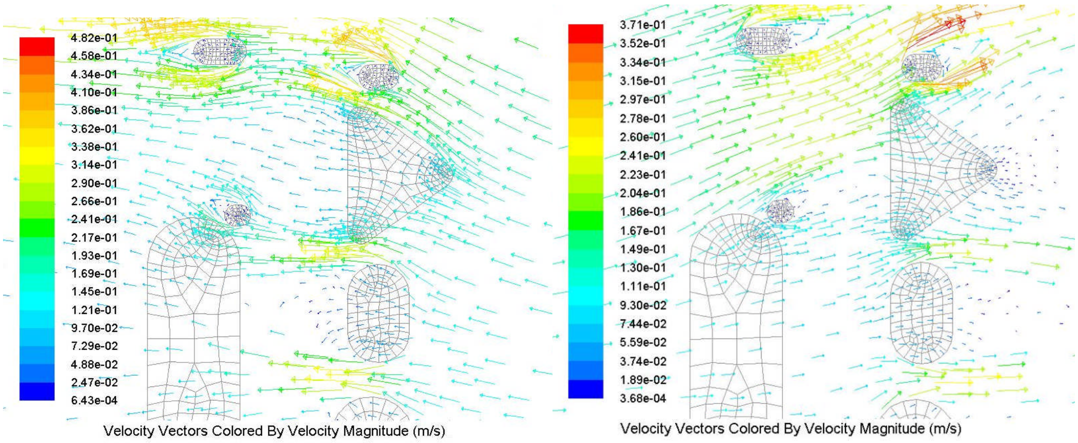
Figure 2- Positions of channels modelled (adapted from Hydrographic Office 1994).



(a) Mean E-W open ocean current speed

(b) Mean W-E open ocean current speed

Figure 3- Flow around the Maldives for the mean W-E and E-W open ocean current speeds.



(a) Mean E-W open ocean current speeds

(b) Mean W-E open ocean current speed

Figure 4- Flow around Male’ and South Male’ for the mean W-E and E-W open ocean current speeds.

There is a limit to the amount of energy which can be extracted from a site without it having a significant impact on the site. This limit is site specific however a 20% limit is often used as an initial estimate of extractable power. The 20% limit may not accurately reflect the amount of power which can be generated without there being a significant impact at the sites. For some sites it may be possible to generate more power and for others less power may need to be generated for the impact to be acceptable. It should also be noted that it may not be technologically or economically possible to exploit all of the extractable power. The amount of power which is technologically and economically exploitable is dependent on the current speed in the channel. At times when the open ocean current speed in the east to west direction is equal to its mean value, the sum of the extractable power in all of the channels modelled is 106 MW. At times when the open ocean current speed in the west to east direction is equal to its mean value, the extractable resource is 28 MW. The reduced power available when the current flow in the west to east direction is partly due to the lower mean current speed in this direction and partly due to the position of North Ari Atoll to the west of Male’ and South Male’. When the flow is from west to east it is slowed by North Ari Atoll before it reaches the Male’ and South Male’ Atolls.

For the mean open ocean current speed in the east to west direction, the channels with the largest extractable resource were Dhiffushi Kandu (31 MW), Gaadhoo Koa (25 MW), Thilafushi (14 MW), Emboodhoo Kandu (13 MW) and Gulhi Falhu (12 MW). For the mean open ocean current speed in the west to east direction the channels with the largest extractable resource were Helegeli Dhekuna Kandu (15 MW) and East of Vadoo Island (9 MW). None of the channels had large amounts of extractable power in both directions, however Gaadhoo Koa (25 MW E-W, 0.23 MW W-E), Emboodhoo Kandu (13 MW E-W, 1.39 MW W-E) and Helegeli Khekuna Kandu (0.94 MW E-W, 15.40 MW W-E) were identified as performing the best. It is apparent from these results that it is not possible to estimate whether a channel is likely to have a large amount of extractable power based on its position. Anticipating the section on marine protected areas in Chapter 3, Gulhi Falhu and Emboodhoo Kandu are on that list and therefore cannot be used for marine energy installations (SARI, 2010).

When interpreting the results from the CUSP model it is necessary to remember that the model is based on a number of simplifying assumptions. In the model it was assumed that the porosity of the atolls was uniform. This is equivalent to assuming that the channels in the atoll rim are uniformly spaced around it. This assumption is more applicable to some atolls than others. The shapes of the atolls were also simplified in the model. These two simplifications will have small effects on the flow pattern around and through the atolls. These simplifications may result in the model predicting a large extractable resource for channels where there is actually only a small extractable resource or predicting only a small extractable resource in channels where there is actually a large extractable resource. As a consequence, whilst the model results are valuable for demonstrating that there is a significant ocean current resource in the Maldives, decisions to exploit the resource in specific channels should not be based solely on the results of the model.

Tidal Currents

Tides are the periodic raising and lowering of the sea level that occurs daily throughout the ocean. Tides are very long and regular shallow water waves with wavelengths of thousands of kilometres and heights which can range to more than fifteen meters (Trujillo and Thurman, 2011). The tidal regime in the Maldives is semi-diurnal with diurnal inequalities. This means that there are two high tides and two low tides of different heights a day. The time between successive high tides is approximately 12 hours and 25 minutes.

In addition to the daily cycle, the heights of tides also vary with a monthly cycle. At new moon and full moon the Moon is aligned with the Sun and the tidal range (the vertical difference between high tide and low tide) is large. The maximum tidal range is called a spring tide. The minimum tidal range is called a neap tide. Neap tides occur when the moon is at right angles to the sun. The tidal range is related to the current speed with larger tidal ranges resulting in faster tidal currents. The time between successive spring tides is approximately 14 ¾ days.

The rise and fall of the tides is accompanied by horizontal water movements, referred to as tidal currents. The tidal current energy resource is dependent on the speed of the tidal currents and the cross sectional area of the channels through which they pass. Tidal currents in channels are driven by a difference in surface elevation between the ends of the channel. This difference in surface elevation is referred to as the head difference. If the head difference is known, the flow speed in the channel can be estimated and, hence, the available resource can be estimated.

Tide data are recorded at three stations in the Maldives: Hanimaadhoo (far north), Hulhule (Male'-central) and Gan (far south) (See Annex III for tide data). Since these three stations are all situated on different atolls, there are no channels for which the variation of head difference with time can be estimated. Therefore, a detailed estimation of the available tidal resource cannot be given.

Other Factors affecting the overall currents

The prevailing wind conditions in the Maldives are determined by the monsoons and it is these winds which drive the ocean surface currents in the Indian Ocean. Local winds can, however, affect the magnitude and direction of the currents if they blow consistently in the same direction for a sufficient duration. An understanding of how local winds affect the overall currents will increase the accuracy with which resource estimates can be made. More details about the wind climate of the Maldives can be found in Annex III containing wind data.

Waves may also have an effect on local currents. Studies by Davies and Xing (2000), Xie et al (2001) and Moon (2005) demonstrate that waves can contribute to local current and sea level changes. It is not apparent from the literature or from interviews with local fishermen, divers and boat captains whether waves have a noticeable effect on the speed of currents within Maldives channels. As such, the accuracy of a resource estimate is unlikely to be greatly reduced by not taking into account the effects of waves on local currents. Annex III gives more information on the wave climate of the Maldives.

There is a large variation in the speed of the currents in different channels in the rims of the atolls. The speed of the flow in a channel is influenced by a number of factors relating to its bathymetry, topography, position and orientation. For the bathymetry the significant factors are the channel width, how linear the channel is and the presence of obstructions, such as thila (outcrops of coral reef extending to just a few meters below the surface). Typically the flow is faster in narrow channels and channels with linear walls. The presence of thila in a channel cause a local increase in the flow speed in the channel. Too many thila may make a site less favourable for energy extraction, however, because they limit the area where devices and their necessary infrastructure can be installed and may make the flow too turbulent for energy extraction.

The topography of the reef structure at either end of the channel is another significant factor. Fishermen, boat captains and divers suggest that the longer the reef structure, the faster the current in the channels at either end of the reef will be.

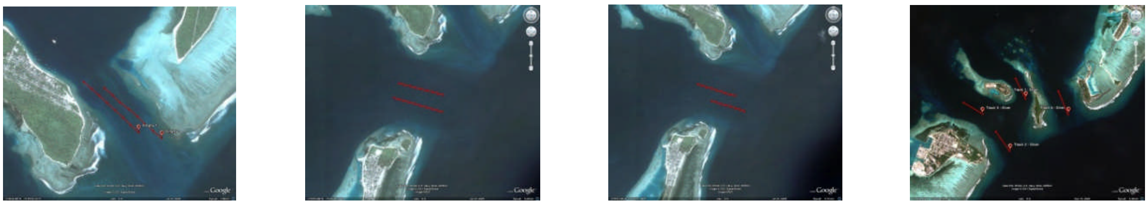
Finally the position and orientation of the channels are reported to have a significant effect on current speed and direction. Currents tend to be faster in the east-west orientated channels than in the north-south orientated channels. The flow direction is also more predictable for east-west channels with westward flowing currents during the northeast monsoon and eastward flowing currents during the southwest monsoon. A more detailed description of the bathymetry and topography is given in Annex III in the bathymetry section.

Overall current resource

The ocean currents and tidal currents have been established to be the major components of the resultant currents although ideally the effect of local wind driven currents should also ideally be taken into account. Of these currents it has only been possible to model the ocean currents. The resource estimates for the ocean current speeds will not give an accurate picture of the overall current resource. Twice a day the tidal currents will be flowing in the same direction of the ocean currents, increasing their magnitude and twice a day they will be flowing in the opposite direction, decreasing their magnitude. The effect of the tidal currents on the overall current will be greatest for spring tides. In addition to estimating the current resource by modelling the magnitude and direction of the components, the overall current resource can be estimated from site measurements.

Surface current measurements were taken in a number of channels in the Maldives. At each site the measurements were taken for short periods of time and so only encompassed a small part of the tidal cycle. This means that whilst it is possible to estimate the available resource for the given times that the measurements were taken, it is not possible to comment on the annual variation of the resource. Maps of the tracks along which measurements were taken are shown in Figure 5.

Emboodhoo Gaadhoo Koa Kuda Kahli (i) Kuda Kahli (ii)



Mulah Mulee (i) Mulee (ii) Thanburdhoo

Thilafushi Keyodhoo Rakheedho

Figure 5- Maps of tracks used in current measurement

The speed of the flow in a channel varies with the distance from the side walls of the channel and the distance from the bed of the channel (Carbon Trust, 2009). The surface velocities were adjusted to reflect these variations and used to estimate the available resource in the channels. It is likely that the current resource in these channels is significantly larger than is indicated by the experimental results. The experiments were carried out in April 2011, a time of year when the currents are relatively slow.

Table 1 shows the extractable ocean current resource for the channels at the time of the measurements. The results from the CUSP ocean current model are also included in Table 1 for the channels for which they are available.

Table 1 Extractable ocean current resources.

Channel	Depth and width averaged flow speed (m/s)	Extractable power calculated from experimental results (MW)	Extractable power calculated from CUSP ocean current model (MW)
Emboodhoo Kandu	0.586	0.25	1.39
Gaadhoo Koa	1.187	5.17	0.23
Kudha Kali	1.168	2.76	0.06
Mulah	1.436	3.57	
Mulee	1.28	7.9	
Himafushi (central)	1.095	0.74	0.07
Himafushi (track 2)	1.121	2.39	
Himafushi (southmost)	1.065	1.37	0.20
Himafushi (northmost)	1.192	1.92	0.16
Keyadhoo	0.464	0.11	
Rakheedhoo	0.125	0.002	

With the exception of Emboodhoo Kandu, the overall current resource calculated from the experimental results was larger than the monsoonal current resource calculated from the CUSP model results. This emphasises the need to take into account all of the factors which affect current speeds when estimating the current resource. It also suggests that the potential resource is much larger than was predicted by modelling just the oceanic currents.

2.1.3 Proven technologies

A large number of concepts for extracting power from tidal currents have been proposed. These devices can be used to generate energy from any type of ocean current; they are not restricted simply to tidal currents. The devices can be split into three main categories: horizontal axis turbines, cross-flow turbines and oscillating hydrofoils. Most devices are at the concept design or laboratory scale prototype phase in development but a few are at an advanced demonstration phase.

Prototype turbines from Marine Current Turbines (2011), Hammerfest Strøm (2011), Open Hydro (2011), Ponte di Archimede (2006), Verdant Power (2009), Atlantis Resources (Nerus turbine) (Atlantis Resources, 2009), Tidal Generation Limited (2010) and Hydra Tidal (Morild, 2010) have all been grid connected. In addition to the grid connected devices a turbine from Clean Current, combined with a battery storage system, has provided power for an island community (Clean Current, 2010) and a device from Pulse Tidal is feeding electricity directly to a chemical plant (Pulse Tidal, 2011). Almost all of the types of turbine are represented in these power generating prototypes. The Marine Current Turbines, Verdant Power and Hammerfest Strøm turbines are horizontal axis turbines which resemble wind turbines. The Clean Current and Open Hydro turbines are also horizontal axis turbines but these are ducted and have a higher solidity than wind turbines. The Ponte di Archimede turbine is a vertical axis turbine. The Pulse Tidal and Atlantis Nerus turbines are designed for shallow water operation. The pulse tidal allows generation in shallow water by being of the oscillating hydrofoil type and hence able to have a large swept area by increasing the width of the device whilst maintaining a small depth. The Nerus turbine is also designed for shallow water sites. The European Marine Energy Centre (EMEC) based in Orkney, Scotland, provides a test-site for full-scale grid connected marine energy prototypes. Whilst only some of the prototype tests mentioned above were carried out at EMEC, EMEC is becoming increasingly popular. Many prominent tidal technology developers have plans to install prototypes there, making it an excellent place to watch and see the latest developments in tidal technology.

When selecting a turbine for use at a specific site a number of factors need to be considered including the range of flow speeds at the site, the site depth and sea bed material. Knowledge of these parameters allows the selection of a turbine with a suitable foundation type and cut in speed.

Environmental impact

Whilst tidal barrage systems have a large impact on the environment, tidal current turbines are thought to be much more environmentally benign. Since ocean current energy extraction is still a nascent industry, the environmental impacts of extracting energy from currents are not yet fully understood (Scott, 2007). Potential impacts include changes to the flow and effects on the local marine ecology. Extracting energy from a current flow in a channel will affect the speed of the flow and, possibly, affect the water levels in the channel. The magnitude of the effect will depend on the amount of energy extracted allowing developments to be be planned so that their impact on the flow is kept to an acceptable level. Extensive monitoring of the effects of the SeaGen turbine in Strangford Lough (Marine current turbines, 2011) has been carried out since 2008. The monitoring has focused on assessing the impact of the turbine on the local wildlife and has demonstrated that the turbine does not have a significant environmental impact (Downey, 2010). Ocean current turbines also have minimal or no visual impact.

2.1.4 Discussion

The resource assessment carried out indicates that the Maldives are likely to have a significant current resource however insufficient data were available to allow an accurate estimate of this resource to be made. The CUSP model of monsoonal current resource demonstrated that the flow around the Maldives is complex and, as such, it is not possible to judge which channels will have a large extractable current resource by considering their position on the atoll rim and their orientation.

Results from the CUSP model also indicated that channels with a large extractable current resource for one monsoonal current direction typically had a much smaller extractable current resource when the monsoonal current was flowing in the opposite direction. It may be necessary to exploit the resource in a number of channels so that the portfolio includes sites with large extractable resources for each direction of monsoonal current flow. Power storage options and alternative ways of generating energy also need to be considered since the magnitude of the current resource varies over the year.

The CUSP model identified Dhiffushi Kandu, Gaadhoo Koa, Thilafushi, Emboodhoo Kandu, Gulhi Falhu, Helegeli Dhekuna Kandu and East of Vadoo Island as sites that may have a large extractable current resource. However, Gulhi Falhu and Emboodhoo Kandu are marine protected areas and therefore cannot be used for marine energy installations. The model was based on a number of simplifying assumptions and so the selection of channels for exploitation should not be based solely on the model results. Local knowledge should be used in conjunction with the model results to select channels with fast flow speeds and more detailed measurements should be made in these channels.

Selecting appropriate turbines for deployment in channels in the Maldives requires a detailed knowledge of the variation of flow speed at the sites. Since the CUSP model-results indicated that there is typically a large difference in the extractable resource in a channel during the northeast monsoon (flows from east to west) and the southwest monsoon (flows from west to east), it is necessary that measurements are taken over a period of time which includes both northeast monsoon currents and southwest monsoon currents. Ideally measurements should be made over a period of a year to give a clearer understanding of the seasonal variations. Current measurements should be made using bottom mounted Acoustic Doppler Current Profilers (ADCPs). In addition to detailed current measurements, detailed bathymetry information and surveys of channel bed material are needed in order to allow a suitable turbine foundation type to be selected.

2.2 Ocean thermal

This section provides an overview of Ocean Thermal Energy Conversion (OTEC) and its potential in the Maldives. Further background information can be found in the Annex Report: Annex VI. OTEC Introduction, Annex VII. OTEC Literature review, Annex VIII. OTEC Available resources and Annex IX. OTEC Technologies.

2.2.1 Introduction to OTEC

The oceans are natural collectors of solar energy and absorb a tremendous amount of heat from solar radiation daily. In the waters surrounding tropical islands such as the Maldives, intense sunlight and long days of sunlight result in significant heating of the upper 35-100m of the ocean, yielding comparatively warm (27-30°C) oceanic surface waters. Below this warm layer the temperature decreases to an average of about 4°C at approximately 1,000m depths (CRRC, 2010a).

This temperature differential represents a significant amount of potential energy, which if harnessed is a renewable energy source. A differential of approximately 20°C between surface and sub-surface seawater temperatures is required for Ocean Thermal Energy Conversion (OTEC) to be feasible (NREL, 1989; WEC, 2007). OTEC converts the thermal energy into kinetic energy via turbines. The turbines can then be used to drive generators, producing electricity (CRRC, 2010a). Unlike most renewable energies, OTEC is base-load: the thermal resource of the ocean ensures that the power source is available day or night, and with only modest variation from summer to winter.

Although the focus of OTEC is on energy generation, several cogeneration products are possible, including desalinization of seawater, mariculture, liquid fuels production (hydrogen and ammonia) and seawater air-conditioning (SWAC), all of which can contribute to its economic viability (CRRC, 2010b).

2.2.2 Overview of available ocean thermal resources

Critical elements to consider in determining the location of an OTEC facility is that it should be within 25 km of an ocean region where there is a temperature difference of about 20°C in the first 1,000 meters below the surface. This distance determines the length of the costly cold water pipe, which represents the single biggest cost item of an OTEC facility (GEF, 2000). It is suggested that for smaller OTEC facilities (<10MW), the resource should not be further than 3 km from shore (Vega, 1992), in order to minimise the infrastructure costs associated with the cold water pipe.

The sea surface temperatures in the near shore waters of the Maldives coast do not vary much throughout the year, with a monthly average generally ranging between 28-29°C and maximum temperatures rarely over 30°C (Hastenrath and Greischar,1989; Khan et al, 2001).

For the required 20°C temperature differential between surface and sub-surface temperatures for OTEC, the sub-sea temperature should be approximately 8°C as a baseline for Maldives. From the available literature on sub-sea temperatures in the Maldives region, it can be concluded that the required 8°C temperature sub-surface temperature occurs at a depth of between 800 and 1,000m (Paul and Ramamirtham, 1963).

Bathymetry, seismic data and extreme weather

Careful OTEC site selection requires a comprehensive knowledge of site-specific bathymetry as well as local climate features inasmuch as they may affect the 20°C temperature amplitude seasonally. OTEC is very sensitive to any loss of thermal resource; with even one degree difference can markedly affect the energy generation potential (Vega, 1992).

Research into potential OTEC installation locations would need to be concentrated on the areas to the east and west of the Maldives, as the inner sea is of insufficient depth (MGDS, 2011). A 1998 study reported the results of echo soundings around 4 Maldivian atolls, one of them being north Male' (Anderson, 1998). They detected steep reef slopes that could contribute to appropriate depths for OTEC (>1,000m) being located within a short distance from land. Should an OTEC facility of <10MW be considered in the Maldives, it would be essential to conduct detailed bathymetry studies to accurately identify areas of 1,000m depths within 3km from shore.

Other elements to consider in determining the location of an OTEC facility are the likelihood of earthquakes and extreme weather conditions. The likelihood of earthquakes with magnitude of 5 and above in Maldives is limited to only the southern parts of the country, namely Huvadhoo and Addoo Atolls (UNDP Maldives, 2006).

Besides heavy rains and strong winds during monsoons, hazardous weather events which can affect Maldives are tropical storms or 'tropical cyclones'. Cyclones are classified according to wind speeds in their circulation. Cyclones are infrequent in the country, and the Maldives have no cyclone classification of its own (WMO, 2003). Only the northern islands of the country are affected by weak cyclones that are formed in the southern part of the Bay of Bengal and the Arabian Sea.

Specific research into Maldivian OTEC potential

There is no field research into the OTEC potential of the Maldives that has been documented, i.e. mapping of the thermal resource or detailed bathymetry surveys. There has only been one preliminary investigation to determine the proximity of appropriate bathymetry to the islands. A group known as Aquarius Rising conducted a preliminary investigation into the potential for OTEC in the Maldives in the late 1990's. This consisted of a chart survey to determine where deep water (>1,000m) was located no more than 3 km from shore, with a preference for proximity to uninhabited islands (Bjelkeman-Pettersson, 1997a). Four 1:3,000,000 scale charts were surveyed, and comment was made of the sparse sounding information in many areas, with little detail within 10 km from shore. Nonetheless, Aquarius Rising listed 10 potential locations (Bjelkeman-Pettersson, 1997b). None of these locations were in Male' Atoll.

The only example of any attempt to develop an OTEC type facility in the Maldives is the Six Senses Soneva Fushi Resort in Baa Atoll, 115km northwest of Male' (Soneva, 2011). It was the first deep-sea water-cooling system ever to be trialled in the Maldives. Deep sea-water cooling is also known by the acronym SWAC (Sea Water Air Conditioning). It is similar to OTEC in that it entails installation of a pipe to depth in the nearby sea with the purpose of drawing up cold water, although in this case it was for cooling purposes, not energy generation. Since conventional electrical air-conditioning in the buildings of the resort contributed to approximately 25 % of the resort's total energy demand, Soneva Fushi – in her attempt to become carbon neutral – wanted to replace these with the renewable option of using the cold water of the nearby depth of the sea. Cold water (11-12°C) was pumped through a pipe from the 300m shelf approximately 3 km southeast of Soneva Fushi Resort. From the pump station, it was distributed to guest rooms and offices via an insulated underground piping system. Non-corrosive fan units in each room enabled the heat exchange between water and the surrounding air to bring the temperature down to comfortable levels. Unfortunately the project had some design flaws that resulted in it not delivering on cooling requirements as anticipated and it was thus decommissioned by Soneva in 2009. One of the problems encountered was that the pipeline wasn't weighted down sufficiently, as with all the weights on it was still floating. Because the anticipated depth wasn’t reached, the water that was pumped in from the deep water intake pipe was not cold enough [Van Zyl, P., 2011. Discussion on Soneva Project. Personal email communications, 17 May 2011].

2.2.3 Proven technologies

An OTEC plant consists of a heat engine that converts thermal energy into kinetic energy through the temperature gradient between a ‘heat source’ and a ‘heat sink, using a similar principle to steam engines, albeit on a smaller scale. There are 3 major OTEC facility designs, open-cycle, closed-cycle and hybrid cycle. In all of the three cycles, it is necessary to obtain deep cold water to condense the working fluid, which is normally available at depths of 1,000m, where the temperature of the water is approximately 4°C (Plocek, Laboy and Martí, 2009).

While closed-cycle facilities are more complex, they are significantly more efficient and result in greater output due to the greater efficiency of the working fluid. To date they are also the most common of the proposed facilities (CRRC, 2010b). The hybrid-cycle combines the characteristics of the closed cycle and the open cycle, and has good potential for applications requiring higher efficiencies for the co-production of energy and potable water (Avery and Wu, 1994).

Depending on the location of the thermal resource, OTEC plants can be land-based, shelf-based or floating. Land based OTEC is appropriate for those cases where the cold water resource is close enough to shore to be reasonably accessible by pipeline, as is the case in the Maldives where the islands are situated on a narrow shelf with steep offshore slopes [Krock, 2006]. A short as possible Cold Water Pipe (CWP) is preferable, given that CWP can represent approximately 30% of costs. The longer CWP length also means greater friction losses, as well as greater warming of the cold water before it reaches the heat exchanger, both of which result in lower efficiency (CRRC, 2010b).

Environmental impact

The environmental impacts associated with OTEC are primarily those associated with the vertical relocation of relatively large water volumes. It is estimated that 3-5m^3/sec of warm surface water and cold deep water are required for each MWe of power generated. A small commercial facility (40MW) would require flows of 120-500m^3/sec (Krock, 2006).

The warm and cold water intakes pose entrainment and entrapment dangers to plankton, fish and mammals. The discharge water will affect the temperature and density of the water into which it is released, causing localized changes to temperature and currents. There will also be a change to the water chemistry and pH in the discharge area, due to the dissolved gases and nutrients within the outflow.

The generation of noise (turbines, pumps, CWP vibration) and electromagnetic fields (from the power cable in floating designs) are a concern due to the large number of marine mammals that use acoustics, such as dolphins, whales, fish, and EMF for communication like sharks and turtles (CRRC, 2010a).

Technical readiness & commercialisation

The proof-of-concept projects (i.e., Mini-OTEC, Japan, Cuba) demonstrated that both cycles are technically feasible and only limited to sizes of no more than about 100MWe by the large diameters required for the cold water pipes (Ninhous, 2010; Vega, 1992). In the case of the open cycle facility, the turbine is presently limited to sizes of no more than 2.5MWe due to the low-pressure steam.

Considering that the Maldives would most likely opt for a land-based facility, one of the primary challenges will be the cold water pipe (CWP). The fabrication methods required for construction of a 10MWe CWP (approximately 7m diameter) are currently available. Although previous OTEC pilot and experimental plants have successfully constructed and deployed CWP's, there is little experience with a CWP larger than 2m - which is what would be required for large commercially feasible facilities. The CWP for a full-scale 100MW OTEC plant is likely to have a 10m radius (Panchal, 2010).

One of the fundamental discussion points amongst OTEC proponents has been whether a pre-commercial plant (between 2-10MWe sizes) is required before a full-scale commercial plant (> 40 MWe) can be considered to be feasible, both technically and financially (Plocek, Laboy and Martí, 2009).

OTEC was conceived over a century ago, yet there are still no operational commercial OTEC plants, and only 1 operational pilot OTEC plant (Hawaii). This is despite numerous feasibility studies and investigations by both countries and private enterprises, none of which have resulted in an actual installation.

One of the main reasons that commercial OTEC power plants have not been built to date is their unfavourable economics in comparison to fossil fuel (Avery and Wu, 1994; Krock, 2006, and Cohen, 1982). A 5-10MW demonstration plant would entail an investment of $200m, with the return on that investment being poor due to it not being of an economical scale [Zolfagharifard, 2011]. Thus the challenge is to finance a capital intensive technology that does not have an operational record. Without operational records from a pre-commercial (~5MW) plant, financing of a commercial sized plant (>50MW) is highly doubtful. The plant would need to be >50MW to be cost competitive in terms of $/kWh (CRRC, 2010b).

2.2.4 Discussion

There is no proven track record of commercial sized OTEC plants. Therefore, it is unlikely that in the near future, ocean thermal energy can be available in the Maldives. However, if OTEC is considered to be an option in the Maldives, it is advised that it would be a cogeneration plant to maximise it outcomes.

Should an OTEC facility of <10MW be considered in the Maldives, it would be essential to conduct detailed bathymetry studies to accurately identify areas of 1,000m depths within 3km from shore to minimise costs for the cold water pipe as much as possible. Furthermore, detailed estimations of both capital costs and electricity production for a potential OTEC site in the Maldives should be made, since any calculation at this moment of time is speculative, given there are no commercial installations.

3. Local context for marine energy in the Maldives

This Chapter summarises the contextual factors for the implementation of marine energy in the Maldives. Annex X in the Annex Report provides the underlying research findings.

3.1 The Maldivian energy sector

3.1.1 Production and consumption patterns

All inhabited islands in the Maldives have electricity. Presently, nearly all the electricity production is based on diesel generators except for a negligible amount from renewable sources. The cost of electricity generation is relatively high compared to other countries in the region because of the dependence on imported expensive fossil fuels, transportation costs, small-scale generating systems and low-density, scattered populations. The 2008 spike in the global oil price saw prices of petroleum fuels in the Maldives almost double (Kesterton, 2010). The high cost of energy is seen by the Government as a major impediment to national development (RoM, 2010).

Despite the Maldives having abundant renewable energy resources, it depends overwhelmingly on petroleum imports for its electricity production. The country has been limited in that it has no conventional energy resources that it can utilise to meet its energy needs. Although the country is expected to continue to rely on imported fuels for most of its energy needs, renewable energy resources such as solar, wind, biomass, biogas & marine energy are recognized as potential energy alternatives (Invest Maldives, 2009).

It is estimated that almost 42% of the diesel oil imported in the year 2009 was used for production of electricity in resorts, 33% was used for electricity production by STELCO, the national utility, and remaining 25% was converted to electricity in local islands and for industrial purposes. The electricity production is decentralised and based on production units of various sizes. Each island of the Maldives has a separate electricity generation based on diesel generators and distribution system providing services to its residents. The fact that the Maldives are almost completely dependent on fossil fuel imports for power generation presents a significant challenge to the goal of carbon neutrality by 2020 (SREP, 2011).

A report published in January 2011 stated that the total installed power capacity of the Maldives is 109.3 MW. With the exception of tourists resorts, energy use has been concentrated in the capital Male' and at the International Airport in Hulhule east of Male' (PWC, 2011). Data obtained from STELCO indicated that in 2009 Male's peak load reached the point where it equalled installed capacity (35 MW). An additional 10 MW generating capacity were added in 2010, which saw the new installed capacity of 45 MW being sufficient to meet the peak load of 37 MW. Male' load curves provided by STELCO indicate a rising demand from 06h00 in the morning to midday (12h00) and mid-afternoon (15h30) peak. Demand then falls slowly again, with a plateau between 18h00 and 20h00, with a slight rise at 21h30 again, followed by a steady drop throughout the evening [direct communication, STELCO].

Resorts consume a significant amount of energy to fulfil their clients' requirements and provide high levels of comfort. Air-cooling, water desalination, electricity and laundry are the major contributors to their energy demand. All resort islands have private electricity production. There are a total of 97 resorts registered in the Maldives as of 2010; however no consolidated data on their energy consumption is available. The cumulative installed capacity on resorts is estimated at ~100 MW (PWC, 2011).

3.1.2 The energy infrastructure

The Maldives have a very fragmented electricity sector with each island having its own electric power generation system and other basic infrastructure. Electricity in the Maldives has traditionally been provided by four different types of suppliers, namely: the State Electric Company (STELCO), Non Government Organizations (NGOs), Island Development Committees (IDCs) and Independent Power Producers (IPPs) (SREP, 2011). Recently, the government has established six regional utilities in addition to STELCO to provide electricity and other services including water and sewage and has started a process of consolidating the power sector (SREP, 2011).

The development of the energy sector in the islands has been hampered by the small physical size of the majority of the inhabited islands. This has created a system of 'mini-grids' as opposed to one national power grid. Each island has its own independent power-houses & electricity distribution networks (MEEW, 2007). Most inhabited islands have had their own IDCs or IPPs to provide electricity to the local community from fuel-driven generators with installed capacity ranging from less than 100kW to 2-3MW. Resort islands operate their own captive systems.

3.1.3 Future developments

A recent report on the Framework for Energy Investment in the Maldives has estimated that the demand for electricity will grow by 8% by 2020 (PWC, 2011). The Carbon Audit report 2009 predicts that electricity demand will double by 2020 (Bernard, Khelil and Pichon, 2009). A recent report forecasts that the electricity load in the Maldives will increase from 79 MW in 2010, to 146 MW in 2030. Of this total, the greater Male' area (Male', Hulhumale', Viligili and Thilafushi) will account for 50 MW (64%) in 2010 and 113 MW (77%) in 2030 (PWC, 2011). STELCO predict a slightly lower expected peak load of 41MW in 2011; with a rise to 51MW by 2015 [direct communication, STELCO].

Given the generally modest electricity demand and geographic spread of the Maldivian islands, the possibility of interconnectivity may not be feasible with perhaps very limited exceptions. Future investments are expected to be in the form of independent mini-grids for each island or group of islands should interconnectivity be reasonably and justifiably cost effective (SREP, 2011).

Northern Utilities (NU) and STELCO have recently undertaken assessments into the feasibility of network interconnection through submarine cabling in the greater Male' area. NU found the costs at a million dollar per km to be unfeasible, although STELCO's report found that network interconnection would be an advantage in certain areas as technical challenges and investment costs and environmental impacts would be less (Kesterton, 2010; SARI, 2010).

3.2 Renewable energy in the Maldives

In the Maldives the national objective is to replace fossil fuels with renewable alternatives by 2019, in order to meet the Carbon Neutral 2020 goal (SARI, 2010). There are currently 11 small-scale renewable energy projects in the Maldives with a total installed capacity of 209.8kW. However, 25% of the installed capacity isn't operational.

The Maldives are blessed with abundant renewable energy resources, but the ongoing energy programmes in the Maldives until recently have had a substantial focus on electricity generation through diesel-run generators. Little attention was given to promoting renewable energy production in remote islands to meet their energy needs. There was a glut of proposed renewable energy projects announced subsequent to the declaration of the Maldives' carbon neutral ambitions. Numerous MOU's were signed, however, the absence of progress in these projects is causing concern. The challenge is that most of the utilities have little experience or capacity to evaluate these renewable energy projects. (SREP, 2011). STELCO recently invited bids for renewable energy generation, as it intends to purchase approximately 20 MW of electricity from renewable sources that will be delivered to the Male' power grid (STELCO, 2011).

To date, the only renewable energy technologies considered in the Maldives have been wind, solar and biogas (Kesterton, 2010). As part of the United States Agency for International Development (USAID) financed South Asia Regional Initiative (SARI), the US-based National Renewable Energy Laboratories (NREL) completed an integrated wind and solar resource assessment (Renné et al., 2003; Elliott et al., 2003). Solar radiations and daylight hours across the country are reasonably good with ample solar PV and solar heating potential existing throughout the country (PWC, 2011; Renné et al., 2003). Wind energy was measured for 14 months during 2003-04 by NREL. With an average annual wind speed of c.4.5 m/s, the average monthly wind resource in the Maldives has been evaluated as 'poor to marginal' (Renné et al., 2003). Large wind turbines would have a dominant physical presence in a small island, noise and flicker disturbance would need to be assessed (Kesterton, 2010). Micro-wind turbines have a far better capacity factor and are suited to mini-grids, however they have smaller annual yields. Biogas potential was explored in 2007. Waste-to-Energy (WtoE) solutions were found to be feasible from a technical, financial & economic perspective only in cases where the waste streams exceeded 15t per day (ERC, 2007). The most accessible and sizable resource is the landfill at Thilafushi, where the biologically degradable waste from Male' is disposed. There is also the option of recovering landfill gas from the area to be utilized for power and heat generation for use by the industries located on Thilafushi (MEEW, 2007).

Most of the renewable energy supply is intermittent; power is variable and is not necessarily readily dispatchable to meet demand calls. Substantially increasing the renewable energy mix and gaining independence from diesel generation is unfeasible without large-scale, affordable and efficient energy storage capacity. Several key technologies are emerging to address the need for long-duration energy storage. Traditional options include pumped hydroelectric storage, compressed air energy storage (CAES), and sodium sulphur (NAS) batteries. Other more recent energy storage technologies are lithium ion (Li-ion) batteries, flow batteries and flywheels. Of the eleven competing energy storage technologies analysed in a recent report by Pike Research, the clean-tech industry analyst firm forecasts that Li-ion batteries will be the fastest growing category for the Stationary Utility Energy Storage (SUES) sector, growing to a $1.1 billion worldwide business by 2018 (Pike Research, 2009).

The regulatory framework

The Maldives Energy Authority (MEA) has the remit of regulating the energy sector but is constrained to regulating the activities of STELCO, the State Electric Company, and part of the activities of the six regional utilities (SREP, 2011). MEA also issues licenses to power producers and is responsible for tariff setting, and preparing engineering and regulatory codes and orders (PWC, 2011). Consensus is that MEA in its current form lacks the proper regulatory framework and legal mandate to effectively regulate the sector in the country's transition towards carbon neutrality (SREP, 2011).

A framework for clean energy investments in the Maldives was prepared recently with technical support from the Asian Development Bank (ADB). 'Clean energy' encompasses renewable energy and energy efficiency. The document includes an overview of the energy sector in the Maldives and greenhouse gas

(GHG) emissions, the role for renewable energy technologies in the Maldives and barriers to its development, provides recommendations on planning, regulation, institutional requirements and detailed studies to be undertaken in order to develop a complete an investment plan for the energy sector (SREP, 2011).

In May 2011 the Cabinet announced it would establish a Renewable Energy Investment Office to come up with economic solutions to the country's energy concerns and expedite implementation of these solutions. The Renewable Energy Investment Office will operate under the Ministry of Economic Development and will assist the government to draw up investment plans and proposals for foreign aid to facilitate investments and support in alternative energy projects in the Maldives (RoM, 2011). Other functions mandated to the Renewable Energy Investment Office include finding and applying appropriate alternative energy solutions and assisting regional utilities companies in seeking investments and capacity building in the area of renewable energy technologies. More details on specific programmes can be founding Annex X.

Protected areas

The Environment Protection and Preservation Act (EPPA) was enacted in 1993 to preserve land and water resources, flora and fauna as well as beaches, lagoons, reefs and all natural habitats. Under this legislation a total of 26 Marine Protected Areas have been declared within which only diving and bait fishing are permitted (SARI, 2010). See also Annex X, Appendix 5, in the Annex Report for a map showing the protected areas. Of relevance to marine energy projects in Male' Atoll, two channels are identified as protected marine areas and can thus not be considered for marine energy development: Gulhi Falhu (west of Viligilli, North Male' Atoll) and Emboodhoo Kundu (South Male' Atoll).

Under the EPPA an Environmental Impact Assessment (EIA) must be submitted before implementing any activity that may have an impact on the environment. The EIA process in the Maldives is coordinated by the Ministry of Housing and Environment (MHE) in consultation with all relevant GOM agencies and the Environmental Protection Agency (EPA).

Engineering skills

Although the country has access to a large pool of talented engineers and other skilled technical workers, they work largely on the resort islands. Kesterton's interviews with chief engineers suggested that pooling practical experiences and experiments in the field of renewable energy in a co-ordinated fashion could provide real cost/time savings for nation-wide deployment schemes (Kesterton, 2010). It has been suggested that a national centre to support technical capacity building, including drafting appropriate PPAs, & designing energy conservation awareness programs is established. Any renewable energy project implemented in the country will require a high level of foreign expertise as well as import of project components. However, the opportunity exists for local capacity building and the development of local fabrication and manufacturing facilities.

The Maldives National University (previously MCHE) offers engineering degrees and maritime studies, which in time will build a locally educated skills base for both renewable energy implementation as well as marine projects (MNU, 2011). There is a unique opportunity for Scottish Universities, such as Robert Gordon University, to partner with the university to encourage capacity building and knowledge sharing in marine energy given Maldives' potential abundance of this resource.

3.3 Socio-economic considerations

Like in many Small Island Developing States, the techno-economic potential of renewable energy technologies (RETs) in the Maldives is substantial. However, it is not certain that these economically viable renewable energy technologies will indeed be implemented and utilised, since this is greatly influenced by various social, institutional and political factors. Many non-technical barriers impede the implementation and diffusion of RETs, which entails a knowledge sharing process as well as adapting technology to meet local conditions. In order to create legitimacy among potential users, politicians, and the general public, there is a strong need for information campaigns and for successful demonstration of renewable energy applications throughout the entire country. Capacity building activities such as training seminars, workshops, business planning, and development of educational material will assist in the uptake. Furthermore, the development of an explicit national policy for renewable energy and the establishment of new institutions to define and implement policy are necessary to gain institutional strength (Van Alphena, Hekkerta and Van Sarkb, 2008).

While much focus is given to cost and technical factors of a Renewable Energy Technology, their structural security and on-going care is reliant on the value placed on it by the community. Communities need to be involved from the outset in the feasibility assessment, especially in how and where the RET will be physically embedded. The Goidhoo case, where the wind project was shut down due to noise, highlights the risk of not doing so (Kesterton, 2010).

Tourism is a significant contributor to the Maldives overall GDP. In 2010 there were almost 800 000 tourists visiting the Maldives, and the revenues this generated represented 34% of the provisional GDP (DNP, 2011). Both wind and solar have high visual footprints, wind more so than solar. Marine renewable energy has the distinct advantage of a number of technologies being completely sub-surface, this with hardly any visual footprint above the waterline – which is advantageous from a tourism perspective.

3.4 Discussion

In general, the Maldives have sufficient installed capacity to meet its current electricity needs. However, shortages are expected in the near future. These expected shortages, mainly in the Male' region, and the climatic and financial cost of continuing to rely on energy generated by fossil fuels provide sufficient incentives to encourage the penetration of renewable energy into the countries energy mix. Renewable energies investigated to date include solar, wind and biogas. Solar shows the best resource potential of these but its implementation is restricted due to space restraints. Despite numerous proposed wind projects, NREL indicates that the Maldives wind resource is 'poor to marginal'. Plans are being developed for a 3-5 MW waste-to-energy plant near the capital Male'.

Chapter 2 of this Main Report on marine energy in the Maldives has shown that in particular marine current energy might provide a potential resource to add to the national energy mix. Marine renewable energy has the distinct advantage of being very scalable, being well-suited to small mini-grid applications in remote communities, as well as larger scale installations for areas of high demand such as Male'. Furthermore, it is the only renewable energy that can have no visual footprint, an important consideration in a tourist dependent country such as Maldives.

While the Government supports adoption of renewable technologies towards achieving carbon neutrality and improving energy cost and security, there remains significant effort required on various planning, implementation and utilisation aspects. Key barriers to renewable energy implementation must still be addressed to create the much-needed market transparency that will encourage investment. A comprehensive enabling framework that includes laws and decrees, strategies and action plans, and funding mechanisms will enable penetration of renewable energy generation in the country. The recent announcement of the establishment of a Renewable Energy Office is encouraging in this regard.

Capacity building and skills transfer by foreign academic organisations and technology providers will lead to local job creation and improve the overall sustainability of the marine energy sector. The development of a successful marine energy sector would assist the Maldives in meeting their 2020 Carbon Neutral goal, whilst also bringing social and economic benefits. These include improved access and cost of energy to the outer islands and reduced exposure to risk of supply issues and fossil fuel price volatility. The high and volatile oil prices have already started creating serious economic and financial difficulties in the Maldives. Annex X in the Annex Report provides a detailed list of barriers in the context of renewable energy technology development in Maldives.

To promote the implementation of renewable energy technologies, the utilities need to be mandated to procure a stipulated percentage of their electricity from the renewable energy sources, with proper enforcement to ensure compliance. The opportunity to develop renewable energy projects under the UN's CDM program should be encouraged. The additional financial revenue generated by carbon credit sales could assist in making the projects financially viable.

4. Future of marine energy in the Maldives

In the context of the Maldivian quest in becoming ‘carbon neutral’, the Centre for Understanding Sustainable Practice (CUSP) of Robert Gordon University looked into the possibilities of marine energy generation in the Maldives as part of the Maldivian renewable energy portfolio. The Scottish Government, who is keen to explore the possibilities of its export of marine knowledge and technology, has funded this study.

After five months of research into the potential of marine energy in the Maldives, including an 11-day fieldtrip, extensive literature research and computational fluid dynamic modelling, CUSP can present the Government of the Maldives and the Scottish Government with a set of well thought out conclusions and recommendations. These conclusions and recommendations given in the following two sections focus on the potential of marine energy in the Maldives and the potential role for Scotland.

4.1 Conclusions: current marine energy likely part of energy portfolio

The current installed capacity based on fossil fuel generation is sufficient to meet the current Maldivian needs. However, shortages are expected, in particular in the greater Male’ capital area, and to deliver on the ambition to become carbon neutral in 2020, a very ambitious transition towards a renewable energy portfolio is needed to meet the future energy needs of the Maldives. Renewable energy sources such as solar and wind have their limitations, mainly due to their impact on the landscape and thus their potential impact on a reduced attractiveness of the tourism sector which forms a third of the Maldivian economy. Marine renewable energy has the distinct advantage of being very scalable, being well-suited to small mini-grid applications in remote communities, as well as larger scale installations for areas of high demand such as Male’. Furthermore, it is the only renewable energy option that can have no visual footprint. CUSP looked into two marine energy options for the Maldives: currents and ocean thermal. CUSP’s research showed that it is likely that in the foreseeable future current marine energy will be part of the renewable energy portfolio in the Maldives, but that it is unlikely that ocean thermal energy will form part of that portfolio.

Marine currents

Field studies and computer modelling suggest that many of the Maldivian island channels have a significant marine current resource. Initial modelling has provided an indication of which channels may be promising for energy extraction. The most applicable technologies for these channels are the devices designed for slower current speeds and shallow water sites.

The CUSP model of monsoonal current resources demonstrated that the flow around the Maldives is complex. The model’s results also indicated that channels with a large extractable current resource for one monsoonal current direction typically had a much smaller extractable current resource when the monsoonal current was flowing in the opposite direction.

Insufficient data were available to allow an accurate estimate of the resource to be made. The monsoonal current model did not take into account the effect of the other factors that affect the overall current speeds, such as tidal currents. Comparison of measurements made during the field trip with results from the monsoonal current model indicates that the overall current resource is likely to be greater than the estimates from the model indicate. This is particularly significant since, due to the timing of the project, the field trip could only be made during the transition period between the two monsoons when current speeds are slower.

Ocean thermal

The required temperature difference of at least 20°C between surface and sub-surface seawater is available west and east of the Maldives to enable ocean thermal energy conversion (OTEC), the inner sea is of insufficient depth. To the west and east of the Maldives, steep reef slopes are detected within a short distance from land that could contribute to appropriate depths (>1,000m) for OTEC. Unlike most renewable energies, OTEC is base-load: the thermal resource of the ocean ensures that the power source is available day or night, and with only modest variation from summer to winter.

However, there is no proven track record of commercial sized OTEC plants and calculations on test site designs of OTEC facilities indicate a very high energy price. Therefore, it is unlikely that in the foreseeable future, ocean thermal energy can be available for the Maldives. Should an OTEC facility be considered in the Maldives, it would be essential to conduct detailed bathymetry studies to accurately identify areas of 1,000m depths within 3km from shore to minimise costs for the cold water pipe as much as possible. Furthermore, detailed estimations of both capital costs and electricity production for a potential OTEC site in the Maldives should be made, since any calculation at this moment of time is speculative, given there are no commercial installations.

Capacity building

The Scottish Government is aiming for the establishment of an industrial sector in renewables based on its ambition to have a 42% reduction in carbon emissions of 1990 level by 2020, it would be a sensible spin-off from the carbon neutral ambitions of the Government of the Maldives to follow a similar strategy. Although the country has access to a large pool of talented engineers and other skilled technical workers, they work largely on the resort islands. Coordination of this pool of knowledge and expertise in combination with development of the maritime studies at the Maldives National University will provide a solid base of capacity for future developments. The Scottish Government could share its experience with the Maldivian Government in developing its renewable energy sector.

4.2 Recommendations: independent detailed resource scoping before engaging with technology providers

Before a decision can be made on what specific marine energy technology can be implemented, CUSP recommends independent, detailed resource scoping of specific channels. This feasibility study into specific sites will need to be accompanied by an integrated approach by the Government of the Maldives in their transition towards carbon neutrality, also campaigns to promote community and societal acceptance of renewable energy in general and more specific that of marine energy need to be initialised, and finally investing in capacity building. These four recommendations are described in more detail in the following sections.

First recommendation: further research in specific channels to define detailed marine resources

The first recommendation is setting out the requirements for further, independent research into the exact details of the available current resource. The conclusion of the pre-feasibility study into the potential of marine energy in the Maldives was that although initial field studies and modelling showed a potential current, it also concluded that insufficient data were available to allow an accurate estimation of this resource.

The CUSP model identified Dhiffushi Kandu, Gaadhoo Koa, Thilafushi, Emboodhoo Kandu, Gulhi Falhu, Helegeli Dhekuna Kandu and East of Vadoo Island as sites that may have a large extractable current resource. However, Gulhi Falhu and Emboodhoo Kandu are marine protected areas and therefore cannot be used for marine energy installations. The model was based on a number of simplifying assumptions and so the selection of channels for exploitation should not be based solely on the model results. Local knowledge should be used in conjunction with the model results to select channels with fast flow speeds and more detailed measurements should be made in these channels. Initial contacts to provide this local knowledge have already been made by the CUSP team.

Selecting appropriate turbines for deployment in channels in the Maldives requires a detailed knowledge of the variation of flow speed at the sites. Since the CUSP model-results indicated that there is typically a large difference in the extractable resource in a channel during the northeast monsoon (flows from east to west) and the southwest monsoon (flows from west to east), it is necessary that measurements are taken over a period of time which includes both northeast monsoon currents and southwest monsoon currents. Ideally measurements should be made over a period of a year to give a clearer understanding of the seasonal variations. Current measurements should be made using bottom mounted Acoustic Doppler Current Profilers (ADCPs). In addition to detailed current measurements, detailed bathymetry information and surveys of channel bed material are needed in order to allow a suitable turbine foundation type to be selected.

Based on the above, we recommend that the follow-up feasibility study consists of three phases:

1. Selection of channels for further research. Start with the list that formed the conclusion of the modelling done by CUSP and supplement this list with local knowledge from divers, fishermen and boat captains. Initial contacts already have been made during the field trip.
2. Detailed measurements in situ:
   - 2a. Take ADCP measurements over a period of a year to achieve a clearer understanding of the seasonal variations.
   - 2b. Parallel to the ADCP measurements, detailed bathymetry and seabed studies must be undertaken to determine the most appropriate anchoring mechanisms for Maldives conditions.
3. Only after a detailed understanding of the available resource is at hand and independent experts have developed in-depth current profiles as a further detailing of the current modelling done by CUSP, will it be appropriate to engage with different technology providers to decide on the most appropriate technology.

Until such time, it is advisable for the Government of the Maldives to remain technology agnostic. Partnering too early with specific technology providers could result in a scenario whereby the Government of the Maldives is obliged to use technology that is not suited to the particular channel and current characteristics, and will not deliver maximum energy at the most economical cost.

Second recommendation: an integrated energy approach

Further investigation of marine energy options should be grounded in an integrated strategy to fulfil future energy needs in the Maldives, establish a future-proof energy portfolio and to make the transition to a carbon neutral nation. The Government of the Maldives made a good start with that integrated approach by establishing the Renewable Energy Investment Office.

To promote the implementation of renewable energy technologies, the utilities need to be mandated to procure a stipulated percentage of their electricity from the renewable energy sources, with proper enforcement to ensure compliance. The opportunity to develop renewable energy projects under the UN's CDM program (and the new Program of Activities) should be encouraged. The additional financial revenue generated by carbon credit sales could assist in making the projects financially viable.

Third recommendation: community & societal acceptation

While much focus is given to cost and technical factors when renewable energy technologies are planned, their structural security and on-going care is reliant on the value placed on it by the community. Communities need to be involved from the outset in the feasibility assessment, especially in how and where the renewable energy facility will be physically embedded. Furthermore, campaigns to promote community and societal acceptance of renewable energy in general and more specific those of marine energy need to be initialised.

Fourth recommendation: capacity building

Capacity building and skills transfer by foreign academic organisations and technology providers will lead to local job creation and improve the overall sustainability of the marine energy sector. The development of a successful marine energy sector would assist the Maldives in meeting their 2020 Carbon Neutral goal, whilst also bringing social and economic benefits. These include improved access and cost of energy to the outer islands and reduced exposure to risk of supply issues and fossil fuel price volatility.

Similar to the Scottish Government aiming for the establishment of an industrial sector in renewables, the Maldivian Government could consider to initiate a similar strategy, it would be a sensible spin-off from the carbon neutral ambitions. The Scottish Government could share its experience in developing such a renewable energy sector. Investing in capacity building through higher education in renewable energy and the development of a renewable energy sector will make the carbon neutral ambitions of the Government of the Maldives future-proof.

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