Andrew Said

Myanmar’s Renewable Energy Potential – Open source resources mapping for electrification of rural communities

Master’s thesis for the degree of Master of Science (Technology) in Engineering submitted for inspection.

Espoo 06.05.2018

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Abstract

Myanmar has one of the lowest electrification rates in Asia, with a clear disparity between urban and rural electricity access. This has led to an energy inequality within the country with many rural communities depending on traditional forms of biomass or expensive alternatives to meet their energy needs. As a result, Myanmar has developed a National Electrification Plan in which aims to provide universal access by 2030. With the plan relying heavily of a centralised grid network, there exist the potential for long grid connection wait times for isolated rural communities.

To address the energy access inequality in Myanmar, many rural communities are looking towards decentralised renewable energy systems, to ensure their energy needs are met prior to grid arrival. This study focuses on the potential for these decentralised renewable energy systems to provide energy from wind, solar, biomass and hydrological resources. This study was undertaken as part of a larger initiative known as the CORE-app, which aims to provide a technical and economic case for the feasibility assessment of the implementation of decentralised energy systems to meet the energy needs of rural communities and achieve the Myanmar Government’s goal of providing universal energy access in the country by 2030.

This study was undertaken as phase 1 of the CORE-app process and was primarily concerned with mapping the country’s renewable energy resources at a high spatial and monthly temporal resolution. These resolutions allowed for the assessment of each respective renewable resources energy potential in reference to each village community location. This study utilised entirely open source data sets, GIS and programming software to ensure the methodology and its subsequent results are freely available to the public and for reproduction on other areas of interest.

The study found that there exists a high potential for renewable decentralised energy systems, with many areas having multiple applicable resources supporting the notion of hybrid energy systems. The study also developed a village energy potential profile which illustrates the energy potential of over 1000 villages, within the Lashio and Kayaing Provinces, and further established country-wide resource potential maps.

With the focus on expanding the grid network to achieve universal electrification, the energy inequality in the country may continue. However, with the establishment of decentralised energy systems, Myanmar has the potential to ensure the continual growth of the country, bridge the energy gap and provide universal energy access to all the population.
Keywords Decentralised Energy Systems, Rural Electrification, Solar, Wind, Hydro-power, Biomass, Open source
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Thank you to Marko Kallio, who guided me through the world of GIS with patience, understanding and continual support. I would also like to thank him for the advice, assistance, and wisdom throughout the entire thesis process and state that without his support the work could not have been undertaken.

I am glad to have the opportunity to work with the CORE-app team on the development of this project and the opportunity to continue on after this study.

Espoo 6.5.2018

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## List of terms and abbreviation

<table>
<thead>
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<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>kWh</td>
<td>Kilowatt hour</td>
</tr>
<tr>
<td>tWh</td>
<td>Terawatt hour</td>
</tr>
<tr>
<td>kWh/day</td>
<td>Kilowatt hour production in 24-hour period</td>
</tr>
<tr>
<td>m s⁻¹</td>
<td>Metres per second</td>
</tr>
<tr>
<td>m³ s⁻¹</td>
<td>Cubic metres per second</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>HydroSHEDS</td>
<td>Hydrological data based on Shuttle Elevation and various scales</td>
</tr>
<tr>
<td>QGIS</td>
<td>Open source geographic information system</td>
</tr>
<tr>
<td>(x)&quot;</td>
<td>Resolution in arc second</td>
</tr>
<tr>
<td>(x)’</td>
<td>Resolution in arc minutes</td>
</tr>
<tr>
<td>Resolution</td>
<td>spatial and temporal, defined in each instance</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic solar system</td>
</tr>
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</table>
Introduction

1.1 Background

Myanmar is presently at a crossroads. Since the country’s political reform in 2010, Myanmar’s growth domestic profit (GDP) has grown from 5.6% in 2011 to 8% in 2015, with a current GDP of 67.4 billion USD (ADB, 2017). The Asia Development Bank (2017) also identified Myanmar as a potential growth country, with the impression that GDP will continue to grow due to outside infrastructure development and the continued opening of boarders to foreign trade and exports.

With this steady economic growth, the Myanmar Government is endeavouring to continue the development of the country in its entirety. Amongst other important issues, access to electricity is at the forefront of the Southeast Asian country’s agenda, with the Ministry of Electric Power and Energy (2016) stating that during the 2016-2017 fiscal year, approximately 37.24% of households consumed energy from the centralised grid system. The actual percentage of residents with access to electricity varies depending on sources and methods employed in the calculations (Kanagawa & Nakata, 2008), and as such other sources suggesting a countrywide electrification rate ranging from 32% – 52% (Pode et al, 2016 & Ostojic, 2016).

Myanmar also faces an issue with energy inequality. With much of the centralised energy infrastructure located in low lying and/or metropolitan areas, there is minimal opportunity for distribution and transmission of energy to rural communities due to topographical and/or remote isolation issues. As such the development of decentralised, off or mini grid, systems may be the most appropriate way to ensure universal energy access in Myanmar. Throughout this study several states, regions or areas experiencing energy access inequality are mentioned. Figure 1 identifies the administrative areas of Myanmar to assist with the localisation of areas throughout this study.
Due to the limited expanse of the national grid system, rural communities are facing energy access issues and a general inequality in comparison to their urban counterparts. This inequality is evident when comparing the disparity between electrification rates of urban and rural communities in Myanmar. As of 2015, the electrification rate of urban communities was 59%, with major cities such as Yangon having a much higher electrification rate (78%). To put this into perspective, the rural electrification rate stands at 18%, with 22 million people in 2017 continuing to have no access to any form of electricity (IEA, 2015 & IEA, 2017).

Considering this economic growth and the need to bridge this energy inequality, the Myanmar Government has an ambitious goal to provide universal electricity access to its citizens by 2030 through the establishment of the National Electrification Plan (NEP). To date, the country’s grid electrification rate has increased from 16% in 2006 to 37.24% in 2017 (Pode}
et al, 2016 & MOEP, 2016). Nonetheless, the goal to achieve the envisioned 100% electrification target appears to be ambitious for a country plagued by an antiquated network and ever-increasing demand.

To achieve universal energy access in Myanmar, there would need to be an additional 7.2 million new household connections by 2030, demanding greater than a doubling of the current rate of expansion (World Bank, 2014). The issue with this is not only the rate of electrical expansion but also the financial burden of said expansion, with the World Bank estimating that approximately 5.8 billion USD is required, not including the generation and transmission investments needed to meet the increasing energy demand (World Bank, 2014).

Furthermore, due to a wealth of renewable energy resources, Myanmar is in a unique position to benefit from the transition to more sustainable energy sources, none more so than the opportunity to create independent decentralised energy systems (off or mini grids) to provide electrical infrastructure to areas which either do not currently have a reliable energy source and/or rural areas which would otherwise be un-electrified prior to grid arrival.

### 1.2 Objective and Methods

This study was undertaken as a collaborative project between Aalto University and the Australian Mekong Partnership for Energy Resources and Energy Systems (AMPERES), to develop an open source Community Renewable Energy Application (CORE-app) which aims to identify the renewable energy potential of every village community in Myanmar.

The CORE-app’s main objective is to provide a technical case for the feasibility assessment of the implementation of decentralised energy systems to meet the energy needs of the community and achieve the Myanmar Government’s goal of providing universal energy access in the country by 2030. The CORE-app also aims to provide an economic case for the implementation of decentralised energy systems for the purpose of rural electrification.

The CORE-app aims to be an entirely open source, freely available, web-based tool, for both local and international renewable energy practitioners to make an estimation of the renewable energy potential, and feasibility of potential hybrid decentralised energy systems for the purpose of rural electrification. To achieve this goal, the CORE-app has a scheduled phased approached to identify the key components and stages of the development of the application.
As such, this study was conducted in reference to the first phase of the CORE-app project, which involved the determination of the renewable resource energy potential of Myanmar. Therefore, the objective of this study is to determine the preliminary renewable energy resource potential of all village communities in Myanmar. The study focuses on the renewable energy potential profiling of Myanmar, with an in-depth assessment of the renewable energy potential of villages within the Lashio and Kyaing provinces, in the Shan and Chin states (Figure 1).

This study identifies Myanmar’s energy potential for biomass, wind, solar and hydropower resources, with the aim to accurately provide a preliminary assessment of the potential energy for the purpose of identifying suitable locations for the implementation of decentralised, or off grid, energy systems.

The significance of this study is the high spatial resolution and the monthly temporal resolution. With a resolution of 30” (approximately 1 km at the equator) and a monthly temporal resolution, this study aims to determine the monthly variation in the renewable energy potential of biomass, wind, solar and hydropower resources. This variation in potential will allow for the development and preliminary assessment of renewable decentralised energy systems that combine variable renewable resources available to each respective village, area, and/or region level.

This study also fills the void of current renewable energy applications which overlook the monthly variation in renewable resource potential. Also, with the lower spatial resolution used in other applications, there is not the possibility to appropriately determine the spatial changes that exist within an area. As such, the CORE-app and this study aim to address these issues and provide the appropriate methodology and procedures to effectively undertake the assessment of renewable energy potential for all areas within Myanmar, whether on a town, region and/or country level.

Figure 2: CORE-App Phased approach
2 Community Renewable Energy Application (CORE-app)

The significance of the CORE-app development is not just in the high spatial and monthly temporal resolution, but also the on-going ability to identify other parameters significant for the assessment of decentralised renewable energy systems for rural electrification.

As shown in Figure 3, the CORE-app provides a multitiered approach which incorporates not just the potential energy supply from renewable energy sources, but also the demand profiling of villages, the economic assessment of decentralised systems, information regarding existing rural energy systems, and the simulation of potential renewable mini-grid options.

The ability to undertake these varied assessments provides a basis for the technical and economic cases into the applicability of decentralised renewable energy systems for rural electrification. In addition to this multi-tiered approach, the collaboration of various organisations who specialise in each of the detailed tiers allows the CORE-app to be a multi and transdisciplinary tool, utilising expertise from Myanmar and around the world.

Figure 3: CORE-app tiered approach
3 Background

3.1 Current Energy Situation

Myanmar is in a unique energy situation. The country suffers from one of the lowest electrification rates in Asia, with only 37.24% of households consuming energy from the centralised grid system in 2016 (MOEP, 2016). Myanmar’s energy situation can be attributed to an over dependence on seasonal hydropower resources, an ever-increasing energy consumption, high transmission and distribution losses due to an antiquated system, and isolated rural communities which have little to no access to any centralised or electricity infrastructure. (Newcombe & Ackon, 2017).

Myanmar’s current electricity output is dominated by hydropower, which accounted for 65% of the total energy production in 2015. Natural gas was the next major source, accounting for 33.4% of the total energy production, with coal representing 1.6% of the electricity output share in 2015 (Emmerton et al., 2016).

With this overdependence on hydropower resources, Myanmar faces dry season energy shortages, with Nai (2014) detailing Yangon required a load shedding of 200 megawatts (MW) during the summer of 2013. Nai (2014) also suggests the peak energy demand in cities such as Yangon, is growing annually at 15% with current energy mixes unable to support this increasing demand. Newcombe & Ackon (2017) further suggest that the over dependence on hydropower leads to a 500-megawatt (MW) reduction in installed capacity. The study further states that due to the antiquated system, overloading and commercial use transmission losses are 6-7%, whilst incurring distribution losses of around 20%.

Myanmar also has an issue with the ever-increasing consumption of electricity. To understand this increase in energy consumption, one merely needs to assess the change in consumption over time. As stated, from the Ministry of Electric Power and Energy (MOEP 2016), in the 2016-2017 fiscal year approximately 37.24% of Myanmar’s population, or 4.05 million households, consumed power from the national centralised grid network, equating to a power consumption increase of 3.24% over the previous fiscal year. Furthermore, when comparing the past and current consumption values it is seen that from 1990 to 2013, the total energy consumption within Myanmar had increased from 1735 GWh to 8714 GWh, with the per capita energy usage increasing from 40kWh to 160kWh, with a current per capita usage of approximately 260kWh in 2016. Myanmar is also confronted with a unique problem of immense grid connections and the subsequent continual increase in the countries energy consumption. As such, it is envisioned that between 2015-2030, the country’s total electricity output will have risen from 14398 GWh to 57654 GWh (Doberman, T 2016 & Emmerton et al., 2016).

As such, the Myanmar Energy Master plan has determined an optimal fuel mix selection which aims at ensuring the future energy demands of the country are met. The plan illustrates a continued heavy reliance on hydropower and coal resources, with the implementation of solar and wind projects. The strategy also indicates a large expansion of current hydropower locations and the development of extensive solar and wind power installations, at the most applicable sites (Emmerton et al., 2016). It can be seen that Myanmar is still heavily dependent on resources which are currently causing issues in terms of reliability and efficiency of the centralised grid network.
One of the major factors affecting the electrification rate of rural communities in Myanmar is the isolation of these communities and the topographic conditions that exist within the country. As Myanmar is dominated by high mountain ranges, much of the centralised grid network has been located in low lying central areas (Figure 4).

![Myanmar's Centralised Grid Network](image)

*Figure 4: Myanmar's Centralised Grid Network (Emmerton et al., 2016)*

As many of the rural communities are located away from this centralised grid infrastructure, these communities have developed decentralised systems which mainly consist of expensive diesel generators. In 2013, of the inhabited 62,218 villages, 2,765 were electrified by a centralised grid system, 14,195 inhabited villages obtaining their power needs from decentralised sources, and 45,258 villages had no access to either a centralised or decentralised energy system (Moe Win, 2013).

The potential to provide energy to these isolated rural communities through decentralised systems is envisioned in the National Electrification Plan (NEP). From Figure 5, it can be seen that to achieve the desired 100% electrification the Myanmar Government has included...
the implementation of decentralised systems, mini-grid and off-grid, to meet the energy needs of the population.

![Figure 5: National Electrification Rollout Strategy (Emmerton et al., 2016)](image)

### 3.2 Urban – Rural divide

Although the current electrification rate of Myanmar is already substantially low, the disparity between urban and rural areas access to electricity is evident with the country’s urban electrification rate of 59%, opposed to the rural electrification rate of a mere 18% (IEA 2015). To put this energy inequality into perspective, the national grid network only provides electricity to approximately 9.5% of all inhabited villages, with the remaining villages depending on other energy sources to meet their usage requirements or continuing to be unelectrified (Pode et al., 2016).

Furthermore, it is estimated that approximately 88% of all Myanmar’s power consumers continue to rely on traditional forms of biomass, being wood or crop residue, to accommodate their cooking needs. It is also estimated that approximately two thirds of all households within the country continue to rely on diesel lamps, batteries or candles to meet their lighting needs (Sovacool, 2013).
As can be seen in the Figures 6 and 7, the 2014 Census clearly demonstrates the equality that exists between urban and rural communities in Myanmar. In urban settings, 77% of households utilize electricity for lighting purposes, while this value is just 15% in rural households. Due to this lack of energy access in rural households, other means of lighting are utilised, such as battery (26%), candles (11%), kerosene lamps (11%) and private generators (21%). These energy mixes, in urban settings, are just a fraction of their rural counterparts with batteries equating to 7%, candles 1%, kerosene lamps 6%, and private generators 6%.

Figure 6: Energy mixes for lighting purposes (Urban households) (data from Ministry of Labour, 2017)
Another indication of the energy inequality that exists within the country is the rate of electrification within different regions. Newcombe and Ackon (2017) found there to be a significant variation between certain areas within Myanmar, with the Kayar region in the south having an electrification rate of 41% as opposed to the Rakhine state electrification rate of 6%. The study also found that many of the remote community locations had a high proportion of villages connected to off-grid or decentralised systems. Also, areas which have abundant renewable resources were seen to correlate with a greater proportion of off-grid village electrification (Newcombe and Ackon, 2017).

Table 1: Village Electrification rates from Newcombe & Ackon (2017)

<table>
<thead>
<tr>
<th>STATE/REGION</th>
<th>ENERGY ACCESS (%)</th>
<th>GRID CONNECTION NUMBER OF VILLAGES</th>
<th>OFF-GRID CONNECTION NUMBER OF VILLAGES</th>
<th>UN-ELECTRIFIED VILLAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>KAYAR REGION</td>
<td>41</td>
<td>53</td>
<td>42</td>
<td>416</td>
</tr>
<tr>
<td>MANDALAY</td>
<td>35</td>
<td>738</td>
<td>189</td>
<td>2 313</td>
</tr>
<tr>
<td>MON STATE</td>
<td>31</td>
<td>254</td>
<td>318</td>
<td>628</td>
</tr>
<tr>
<td>KACHIN STATE</td>
<td>26</td>
<td>1</td>
<td>283</td>
<td>2 295</td>
</tr>
<tr>
<td>BAGO REGION</td>
<td>23</td>
<td>309</td>
<td>2 070</td>
<td>2 416</td>
</tr>
<tr>
<td>KAYIN STATE</td>
<td>23</td>
<td>46</td>
<td>79</td>
<td>1 938</td>
</tr>
<tr>
<td>SAGAING REGION</td>
<td>22</td>
<td>624</td>
<td>3 060</td>
<td>2 295</td>
</tr>
<tr>
<td>CHIN STATE</td>
<td>16</td>
<td>-</td>
<td>326</td>
<td>1 026</td>
</tr>
<tr>
<td>AYARWADDY</td>
<td>10</td>
<td>343</td>
<td>2 992</td>
<td>8 602</td>
</tr>
<tr>
<td>SHAN STATE</td>
<td>9</td>
<td>374</td>
<td>786</td>
<td>13 424</td>
</tr>
<tr>
<td>TANINTHARYI</td>
<td>9</td>
<td>573</td>
<td>1611</td>
<td>2588</td>
</tr>
<tr>
<td>RAKHINE STATE</td>
<td>6</td>
<td>-</td>
<td>1033</td>
<td>2827</td>
</tr>
</tbody>
</table>
Statistics given in Table 1 clearly identify the energy access inequality that exists within the country. Although not stated in the census data, it could be theorised that although there are rural households which have energy access, this access is predominately utilised for lighting purposes.

Although the extent of energy inequality in Myanmar is thoroughly documented, the variation in the number of villages and/or rural communities and the subsequent electrification rate assessment varies significantly between sources. As such, energy equality may differ significantly from research values with some areas having varying electrification rates and energy access issues.

Energy equality is more than just access to energy, as it has been shown that energy access is inextricably linked to the development, health promotion and stability of an area. Kanagawa and Nakata (2007) explain that energy access and poverty are linked, with the access to energy the driving factor in reduction of poverty in rural areas. The study also found a correlation between energy access and the improvement of other socio-economic factors such as gender equality, environmental and community health improvement, reduction in child mortality rates and the increase in childhood education, and community development (Kanagawa & Nakata, 2007).

The idea of energy access and the subsequent improvement of rural communities is also observed in the study by Cecelski (2002), who stated that energy access in rural communities is comparable to food and water security. The study further mentioned that policies which benefit the community must consider energy access to be successful. Kaygusuz (2011) further identified that access to energy had a positive correlation to income development and rural development through the electrification of agricultural processes and the subsequent establishment of rural industries.

Therefore, it could be said that the access to electricity may have the potential to alleviate not just the energy inequality that exists in Myanmar, but also provide an opportunity for the development of rural communities within the country.

### 3.3 National Electrification Plan

As a result of the current energy situation, the Myanmar government has implemented the National Electrification Plan (NEP) in which aims to electrify 100% of Myanmar by 2030. This equates to connecting approximately 7.2 million households to a nationally organised, maintained and regulated centralised grid network, or providing decentralised solutions until grid arrival or indefinitely in isolated situations (Castalia, 2014). The Myanmar NEP, which was approved in 2014, has set the following national energy sector policies to ensure development of the country’s electrical sectors and achieve the goal of 100% electrification by 2030:

(i) Implement short and long-term energy development plans, relying on systematically examined data on energy resources that can be utilised with minimal harm to the environment or persons.

(ii) To ensure private sector participation and privatisation of state energy organisation.
Determine domestic demand and supply of various energy resources in Myanmar.

Programs that support local benefits of energy reserves discovered in their respective areas.

Promote the use of the utilising renewable energy resources for the sustainable energy development of Myanmar.

Promote efficient use and conservation of energy resources.

To promote energy efficiency and energy conservation.

To establish and promote international assistants and developments to ensure continual best practises and the longevity of energy infrastructure in Myanmar.

To successfully ensure the implementation and to achieve the goal of universal energy access in Myanmar, the NEP is set out in a two-pronged approach. The first being the rapid expansion of the national grid and the second being the establishment of decentralised systems for rural and/or remote communities, which would otherwise have to wait substantial periods prior to the arrival of the grid. By undertaking this approach, it is envisioned that by 2020 50% of the nation would have access to energy, increased to 75% in 2025, and ultimately 100% by 2030. The NEP states that the implementation of decentralised systems will be rolled out to remote communities where grid arrival is not envisioned for at least 10 years (Castalia, 2014).

As of June 2017, there have been some significant advancements in rural electrification, with 1354 Community electricity connections (to grid or off grid systems), 6763 public lighting installations, 353 500 people provided with access to electricity, and 70 700 households served by solar power infrastructure. Though this is an impressive start, the current values are well below those figures hoped to be achieved by 2021 under the NEP. Of the anticipated 23 000 community electricity connections (grid or off-grid) by 2021, only 6% have been implemented to date. These same issues are also seen throughout the other anticipated results with only 36% of the targeted public lighting installed, just 6% of the targeted 6.21 million people provided with access to electricity from household connections (Ostojic, 2016).

Although the role of decentralised energy systems is addressed in the NEP, the role of a centralised grid network continues to be the main approach to achieving 100% electrification. It is envisioned that the consolidation of the national grid network will provide electricity to 98% of the population, with decentralised systems rolled out as a temporary measure to rural communities prior to grid arrival and subsequent connection. This approach does not consider the role of decentralised, mini or off grid, energy systems have on the opportunity for not just the electrification of rural communities, but the socio-economic benefits that come with the energy independence of decentralised energy systems.

The exclusion of the long-term viability of decentralised energy systems for rural electrification may be due to the lack of evidence supporting the establishment of decentralised energy systems. Although there have been some qualitative efforts to estimate Myanmar’s decentralised energy potential (Pascale et al., 2016), there has not been significant empirical evidence to assess and/or support the potential for viable decentralised energy systems in all rural villages in Myanmar.
This lack of significant data regarding the potential of decentralised energy systems for the purpose of rural electrification provides an incentive for the development of the CORE-app, which could be used to support the technical, economic and feasibility case for the potential electrification of rural communities through renewable decentralised energy systems.

### 3.4 Rural electrification through decentralised renewable energy systems

Due to relatively long centralised grid connection wait times, and the general unreliability and inconsistency of energy provided by national grid systems in the developing world, the establishment of decentralised systems may be the most appropriate method to meet the energy needs of rural communities and provide an economic standpoint to allow the socio-economic advancement of rural communities (Cader, 2015).

The benefit of decentralised systems for the electrification of rural communities is not just in the energy access and socio-economic benefits, but the opportunity to provide clean reliable energy from varying renewable sources. Renewable resources allow the system to operate without the constant monetary and operating need of fossil fuels.

Furthermore, due to an abundant nature of potential renewable energy sources, Myanmar is in a unique position to benefit from the change to renewable resources for the purpose of rural electrification. The World Bank (Ostojic, 2016) recognised this idea, where they proposed, under the NEP, a total of 11 400 community energy connections to purely decentralised renewable mini/off grid systems by 2021. This equates to 2 282 500 people connected to renewable mini/ off-grid energy systems.

Additionally, Myanmar has a long history with renewable decentralised energy system for rural electrification. During the 2015-2016 fiscal year, of the 4 244 villages with household electrification rates of 70%, 1 837 villages obtained their energy needs from renewable decentralised energy systems. Of the villages with electrification rates of less than 70%, 3 658 villages obtained energy from purely decentralised renewable energy sources (Greacen, 2017).

### 3.5 Renewable Energy potential

The abundance of renewable energy resources in Myanmar supports the feasibility of renewable decentralised energy systems for rural electrification. As mentioned above, there is already a substantial number of decentralised energy systems which utilise entirely renewable resources such as biomass, wind, solar and hydropower.

#### 3.5.1 Biomass

Myanmar has a wealth of biomass resources suggesting biomass could be one of the most viable and abundant potential renewable energy sources. With approximately 52.5% of the country’s land covered by forests and/or mangrove swamps. This equates to a sustainable potential annual yield of over 19 million cubic tonnes of wood fuel (Pode et al, 2016). Furthermore, with the abundance of crop residues produced from varying cultivated crops
throughout the year, the combination of wood fuel, charcoal, and traditional biomass ac-
counts for approximately 90% of the rural populations energy consumption (Sovacool,
2013).

With 70% of the population involved in agriculture, primarily through farming practices, the
report by the Ener and Devel (2015) found that from the annual tonnage of rice husk, rice
straw, corn cobs and other agricultural residues there would be sufficient materials to gen-
erate 60 000 GWh of electricity per annum.

With many rural communities primarily undertaking agricultural practises, there is a signif-
ificant potential for rural electrification from biomass residues. Pode et al, (2016) also demon-
strated that there is a viable financial model due to the ability of rural communities to provide
adequate energy for the processing of crops and the electricity needs of the community.

3.5.2 Wind

The renewable energy potential of wind resources in Myanmar is often overlooked due to
the unfavourable conditions for large scale wind installations. Nonetheless, Myanmar has
shown some considerable potential for wind power, with an estimated installed capacity of
33 gigawatts (GW) and a theoretical generation capacity of 80 tWh per year (Ener and Devel,
2015). Other sources suggest there is a much higher theoretic wind potential, with Hlaing
(2012) observing a theoretical energy potential of 365.1 tWh per year.

The theoretical wind potential also differs significantly throughout Myanmar, with moun-
tainous regions, elevated central areas, and low lying coastal regions within Myanmar having
the most potential for wind power installations.

The principal factor affecting the potential development of wind power resources in Myan-
mar, is the low average wind speeds and corresponding applicable areas. With only 3 400
square kilometres with sufficient wind speeds (>6m/s⁻¹) for feasible large-scale wind instal-
lations, the suitability of large scale installations seems unlikely (Ener and Devel, 2015).
However, with smaller decentralised wind installations, there are potentially more suitable
areas for small turbine installations. As small wind turbines require lower wind speeds, the
areas with sufficient wind speed in Myanmar increase dramatically.

Furthermore, due to the relative small number of wind installations within Myanmar much
of the feasibility of wind resources is not significantly understood. It is estimated there are
only 25 wind power plants within Myanmar, with the number of small scale installations
unknown (Hlaing, 2012). As such, there exists an opportunity to determine the theoretical
wind energy potential for small scale wind installations.

3.5.3 Solar

The abundance of solar resources in Myanmar is evident through the countries geographical
location. Myanmar has an abundance of solar resources through the year and as such the
theoretical energy potential of solar energy within Myanmar is approximately 51,973 tWh
(Kyaw et al.,2011).
One of the main factors affecting Myanmar’s solar energy potential is the topographical conditions of the country. As many of the rural villages are located in mountainous areas, there is a suitability issue of standard photovoltaic installations. Nonetheless in the 2015 - 2016 fiscal year, there were 150 villages within the country which achieved an electrification rate of 70% due to decentralised solar energy systems (Greacen, 2017).

Additionally, with the proposed 465 500 households to be provided energy from decentralised solar off grid energy systems under the NEP, it reassures the potential of solar resources in Myanmar.

### 3.5.4 Hydro

With 65% of energy generation coming from hydrological resources, Myanmar is a country heavily dependent on their hydropower resources. Although an over dependence on the resources has caused the unreliability and inconsistency of energy during the dry season, it appears Myanmar has a vast wealth of hydropower potential.

Kattelus et al., (2014) identified that Myanmar has a hydropower potential of 39 720 MW, with continuous hydropower developments being undertaken with an additional estimated capacity of 12 710 – 38 000 MW. The study further identifies that only approximately 6% of the hydropower potential has been installed developed to date, with much of the larger scale developments aided financially by countries such as China and other countries dependent on imported energy.

Myanmar has a unique opportunity to benefit from varying scales of the plentiful hydropower resources that exist within the country. Sasaki et al., (2015) describes the potential of mid-sized (up to 10 000 kW) hydropower installation for the purpose of decentralised mini-grid developments. The study further states that due to the expansiveness of the country’s waterways and associated tributaries, there is the vast potential for hydropower installations.

As detailed in the above section, there are many rural communities and villages already utilising hydropower resources to meet their energy needs. As such, it would be sufficient to state that it appears Myanmar will remain a country dependent on hydropower resources in both a centralised and decentralised energy context.
4 Methodology

The aim of this thesis is to provide the theoretical renewable energy potential for four renewable energy sources throughout Myanmar on a 30 arc-second (30") spatial resolution (approximately 1 km at the equator) and monthly temporal resolution. By using this resolution, the application provides an in-depth indication into the most applicable times and optimal mixes of renewable energy sources for the use of developing decentralised energy systems for rural and non-electrified communities.

The methodology throughout this study utilised entirely open source dataset and software, which are freely available through varying databases and literature sources. The GIS aspect incorporated the open source software QGIS (QGIS Development Team, 2018), and freely available add-ons to define and project the renewable resource data over the applicable time scale. Calculations were undertaken within R software (R Core Team, 2017).

The ultimate goal for the CORE-App is not only to provide the renewable energy potential for Myanmar, in its entirety, but to also provide the methodology to undertake similar energy assessments on any other region/s of interest.

4.1 Assessment area

As this initial stage of the CORE-App was focused on providing the renewable energy potential of the country, in its entirety, all administrative areas in the Republic of Myanmar have been assessed. This was to ensure the inclusion of surrounding islands and other inhabited land masses which may have be excluded in a mainland study.

In this preliminary assessment, the village specific renewable energy potential was assessed, with all villages identified in the 2014 census being included in this study. In essence, all villages whether electrified or not, were included in this study and as result, this study has identified the preliminary renewable energy potential of all identified. 36 213 villages in Myanmar.

Figure 8 identifies the administrative boundaries of Myanmar and the applicable villages assessed within this study.
Figure 8: Myanmar Administrative Boundaries and Villages (data from Ministry of Labour)
4.2 Biomass

The potential energy characteristics of biomass was determined using historic crop datasets, literature values and the authors own calculations. The biomass analysis focuses solely on the kilowatt hours (kWh ha\(^{-1}\)) of theoretical energy production per harvested hectare. As each respective village crop production varies over time, it was not possible to effectively determine a reliable monthly resolution for biomass energy production. As a result, this analysis aims to identify an infield calculation method which can produce a detailed biomass estimate, with minimal information input from the village.

4.2.1 Biomass Conditions and Assumptions

The objective of this analysis is to determine the theoretical biomass energy potential of agricultural resources within Myanmar. This study does not consider any products grown for biofuel or energy and primarily focuses on agricultural residues, as to not promote the use of mangrove or forest resources and to ensure that food security was at the forefront of agricultural practises in Myanmar.

This analysis also solely focuses on the major crops produced in Myanmar, being maize, rice and sugarcane. In future stages of the CORE-app, millet, cassava and other significant agricultural productions will be analysed, however for the purpose of this study only the above three (3) major crops were assessed.

This theoretical biomass calculation utilises historic and current yield and production values as the main variables. Other factors such as surplus availability factor (SAF), energy usage factor (EUF), and lower heating values (LHV) have been employed from varying literature sources (definitions defined in section 4.2.2).

The theoretical biomass energy potential is given in kilowatt hours (kWh) of energy production per harvested hectare. As such, with the development of the infield analysis, the villages can simply be asked approximately how many hectares and the crop/s that are harvested in the community.

An annual time scale was used. The resolution utilised in this analysis is five (5’) arc minutes. All data inputs, processes and results obtained through this analysis utilise the long term annual average crop production in tonnes per hectare, hectares harvested, and five (5’) arc minute resolution.

4.2.2 Datasets

Earth Stat data

Historic annual harvested (hectares) crop areas and tonnes per hectare were obtained from the study by Monfreda et al (2008). The study visualises the historic annual mean value of hectares harvested and the subsequent yield per hectare, from the period 1997 -2013.

Monfreda et al (2008) utilised data from the Food and Agriculture Organisation of the United Nations (FAO) to identify arable and cultivated lands on a global scale. From this study it is
also possible for the analysis of a total of 175 crops, however for the purpose of this study only maize, rice and sugarcane are assessed. The processes and principles behind the development of the utilised dataset is available from the above-mentioned publication.

**Literature data**

To determine the annual theoretical biomass energy potential, the following factors were required:

- **Residue to Product Ratio (RPR):** determines the biomass produced as a by-product of crop production and processing. In general, it determines the amount of unused biomass material after harvesting and processing.
- **Energy Use Factor (EUF):** amount of current residue being utilised as fuel, whether for cooking, lighting or other.
- **Surplus Availability Factor (SAF):** the amount of surplus material to the amount of residue generated and current use factor.
- **Lower Heating Value (LHV):** the net calorific value of a fuel, determining the amount of heat released by the combustion of a specified amount.

These factors were gathered from a variety of literature sources regarding the use of biomass in South East Asia, Africa and varying other developing countries. The numerical values used for the above criteria are detailed below. As observed in the Table 2, there is no EUF for maize stalk and maize husk. As such, the EUF for maize cob is used.

To ensure the appropriate annual theoretical biomass energy potential, each of the crops analysed were divided into the main agricultural residue produced from each respective crop. Therefore, the crop residues were subdividing into the following:

- **Rice**
  - Rice Husk
  - Rice Straw

- **Sugarcane**
  - Tops and trashes
  - Bagasse

- **Maize**
  - Cob
  - Stalk
  - Husk

The biomass materials were divided in these groups as many of the materials are used for varying activities. For example, rice straw and sugarcane bagasse have a much higher energy use factor when compared with the other residue materials. As such, it would be unproductive to calculate the biomass energy potential, without considering the energy potential of crop residues not currently utilised for resident’s energy needs.
### Table 2: Agricultural Residue Factors  
(Koopmans and Koppejan, 1997)

<table>
<thead>
<tr>
<th>CROP</th>
<th>Residue to Product Ratio</th>
<th>Reference</th>
<th>Energy Use factor</th>
<th>Surplus availability</th>
<th>Lower Heating value (LHV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice (husk)</td>
<td>0.27</td>
<td>Ener &amp; Denvel (2015)</td>
<td>0.531</td>
<td>0.469</td>
<td>12.85</td>
</tr>
<tr>
<td></td>
<td>0.267</td>
<td>Bhattacharya et. al. (2005)</td>
<td>....</td>
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<td>...</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>0.2685</strong></td>
<td></td>
<td><strong>0.531</strong></td>
<td><strong>0.469</strong></td>
<td><strong>12.85</strong></td>
</tr>
<tr>
<td>Rice (straw)</td>
<td>0.33</td>
<td>Ener &amp; Denvel (2015)</td>
<td>0.000</td>
<td>0.684</td>
<td>8.83</td>
</tr>
<tr>
<td></td>
<td>1.757</td>
<td>Otchere-Appiah &amp; Hagan (2014)</td>
<td>....</td>
<td>....</td>
<td>...</td>
</tr>
<tr>
<td><strong>Average</strong></td>
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<td></td>
<td><strong>0.000</strong></td>
<td><strong>0.684</strong></td>
<td><strong>8.83</strong></td>
</tr>
<tr>
<td>Sugarcane (tops and trashes)</td>
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<td>Ener &amp; Denvel (2015)</td>
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<td>0.986</td>
<td>6.82</td>
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<td></td>
<td><strong>0.000</strong></td>
<td><strong>0.986</strong></td>
<td><strong>6.82</strong></td>
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<tr>
<td>Sugarcane (bagasse)</td>
<td>0.25 (bagasse)</td>
<td>Ener &amp; Denvel (2015)</td>
<td>0.793</td>
<td>0.207</td>
<td>6.43</td>
</tr>
<tr>
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<td><strong>Average</strong></td>
<td><strong>0.31</strong></td>
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<td><strong>0.793</strong></td>
<td><strong>0.207</strong></td>
<td><strong>6.43</strong></td>
</tr>
<tr>
<td>Maize/corn (cob)</td>
<td>0.25</td>
<td>Ener &amp; Denvel (2015)</td>
<td>0.193</td>
<td>0.670</td>
<td>16.63</td>
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<tr>
<td></td>
<td>0.273</td>
<td>Bhattacharya et. al. (1989)</td>
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<td></td>
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<td><strong>0.193</strong></td>
<td><strong>0.835</strong></td>
<td><strong>15.75</strong></td>
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<td></td>
<td>2.0-2.3</td>
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<td>1.0 - 2.5</td>
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<td>....</td>
<td>1.00</td>
<td>14.70</td>
</tr>
<tr>
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<td><strong>....</strong></td>
<td><strong>1.00</strong></td>
<td><strong>15.105</strong></td>
</tr>
<tr>
<td>Maize/corn (husk)</td>
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<td></td>
<td>....</td>
<td>15.56</td>
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<tr>
<td></td>
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<td></td>
<td>0.2</td>
<td>Otchere-Appiah &amp; Hagan (2014)</td>
<td>....</td>
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<td>17.2</td>
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<td><strong>....</strong></td>
<td><strong>16.38</strong></td>
</tr>
</tbody>
</table>
4.2.3 Processes and Calculations

From the above-mentioned datasets, it was possible to determine the annual kilowatt hour of theoretical energy production per harvested hectare (kWh ha\(^{-1}\)). The equations utilised in this analysis were obtained from the study by Ener and Devel (2015).

Initially, the residue amount of each crops was calculated using Equation 1 and the average RPR from the values presented in table 2.

\[
R_{prod} = p_{crop} \times RPR
\]  

\(1\)

Where, \(R_{prod}\) is the tonnes of generated residue, and \(p_{crop}\) is the annual average produced crop (t h\(^{-1}\))

From this calculation, each five (5) arc minute cell is given a value for each of the respective crop residues. All areas with no crop production were removed from the calculation through assigning these areas as no-data values. As such, the calculation only considers areas which produce the three major crops being assessed.

Each of the crop residues were then converted to kilograms per hectare (kg/h\(^{-1}\)) with Equation 2.

\[
EP_{res} = (R_{prod} \times 1000) \times (SUF + EUF) \times LHV_{res}
\]  

\(2\)

Where, \(EP_{res}\) is the energy production per residue type.

From this calculation, each agricultural residue is presented in mega joules of energy potential per hectare (mj h\(^{-1}\)). To ensure a consistent unit, being kWh, \(EP_{res}\) was multiplied resulting by a factor of 0.277778.

For the further analysis of potential hybrid renewable energy systems, the theoretical biomass energy potential has not been considered on the following village level analysis.

4.3 Wind

The potential wind energy characteristics of Myanmar were determined using historic synoptic weather measurements, literature limitations, climate models and author calculations. The aim is not to define the processes and principles behind wind energy but to provide the appropriate information to identify the wind energy capacity and most applicable areas for wind installations in Myanmar for the purpose of electrification of rural and/or off grid communities.

4.3.1 Wind Conditions and Assumptions

The objective of this section was to determine the theoretical monthly energy potential of wind resources for rural electrification. This study does not account for the possibility of large scale wind power installations and as such the limiting factor used in this analysis have been detailed below.
This study focuses on wind speed, terrain and turbine limitations as the main variables affecting potential wind energy resources to provide an appropriate indication of applicable areas and capacity of small scale wind installations. The potential capacity of wind energy is given as kilowatt hours per day (kWh/d).

The theoretical wind energy capacity is presented on a monthly temporal, with a spatial resolution of 30". All data inputs, processes and results obtained through this analysis utilise the daily long-term monthly time scale and 30".

4.3.2 Datasets

Historic Wind measurements

Historic daily total wind speed measurements were obtained from an application known as ‘climate robot’ developed by Weather Online. This climate application calculates the long term monthly average (of daily sums) wind speed from available data and provided a value based on the above criteria.

For the purpose of this study, only weather monitoring stations with continuous data from 1998 – 2018 were selected, as to ensure the validity of the monthly averages. As a result, a total of thirty-two (32) weather monitoring stations were selected with seventeen (17) located in Myanmar, nine (9) located in Thailand, two (2) in Bangladesh and one (1) in India. The below figure details the locations of the weather monitoring stations with historic wind speed measurements used in this study.

Figure 9: Location of Weather Monitoring Stations used in this analysis.
Furthermore, it should also be noted that due to the selection of the applicable meteorological monitoring stations, there are large areas within Myanmar which have no applicable data. As a result, global climate data was used to address these areas and the potential inconsistency of meteorological measurements.

**World Climate Data**

Due to the large areas within Myanmar without applicable historical meteorological data, additional data was used to ensure the reasonable assessment of wind speeds within the country. This data was obtained from the study by Fick & Hijmans (2017). The study produced open source datasets of varying spatial resolutions for the use in ecological modelling and GIS analysis.

The World Climate data utilises long term monthly averages of historic wind measurements (1960-1990 & 1920 - onwards) from 12831 weather monitoring stations globally. Of these weather stations 10149 were used for the calculation of wind speeds. The resulting values produce a monthly 30° spatial resolution of monthly global average wind speeds. The wind speed measurements were taking at varying heights, as per the weather stations location and as such the study suggests a generalised 200 m measurement point should be implemented. The processes and principles used in this study can be viewed in more detail from the above-mentioned paper.

Regarding the validity of the climate data, it should be known the Fick & Hijmans (2017) study suggests a relatively high accuracy of calculated wind speeds, with a r value of 0.759. Therefore, the climate data is of an appropriate validity to be used in this analysis, with the study identifying locations that are further from the coast having a higher accuracy. This ensures that appropriate wind speed values are implemented in aforementioned areas of concern.

![Historic Wind Speed Measurements](image)

*Figure 10: Historic Wind Speed Measurements (data from Fick & Hijmans, 2017)*
Global Wind Atlas

The Global Wind Atlas (GWA) is an opensource, interactive web-based application which was developed from a collaboration between the Department of Wind Energy at the Technical University of Denmark and the World Bank. The application aims to provide stakeholders with opportunity to identify potential high wind areas for the use of power generation.

The GWA utilises data from several atmospheric reanalysis sources. This reanalysis is a method the develops a comprehensive record of the changes in weather and climate over time. The GWA also incorporates various climalogical statistics of the datasets to create location specific wind averages which are based on the climalogical parameters of the given location. The processes and principles behind the development of the GWA can be views in more detail from the GWA methodology and dataset section available on the official website (https://globalwindatlas.info/).

For the purpose of this study, the annual average wind speed at 50 m from the GWA was used. The annual average data was displayed on a 30\” resolution and was primarily used validation in the calculation of the average monthly wind speeds.

Figure 11: Annual Wind Speed Average (GWA) (data from Energy, 2016)
4.3.3 Processes and Calculations

Interpolation of no data areas

In order to generate the monthly average wind speed from the available datasets, the data needed to encompass all land areas within Myanmar. It was observed that in areas surrounding the coastline and associated islands the wind datasets did encompass the entirety of these areas.

As such, the historic wind measurements were interpolated to ensure entire coverage of Myanmar and its administrative boundaries (Figure 8). For the purpose of this study, Inverse Distance Weighting Interpolation (IDW) from the SAGA package in QGIS was employed. The aim of this interpolation was merely to assign no data points (areas with no historic wind measurements) to an appropriate value depending on the areas surrounding cell values. As this study utilises a 30” resolution, the no data points only need to be influenced by the cells immediately surrounding the respective cell. As QGIS was employed in this study the following parameters need to be addressed:

1. **Inverse distance Power (P):** identifies the significance of surrounding cells on the interpolation value. The higher the p value, the less influence the interpolation takes from distant points. The value used in this study is 2.
2. **Search Radius:** identifies the surrounding input points which will be used for the interpolation. The number of points used in this study varied depending on the interpolation. For the interpolation of the historic wind measurements a search radius of 100 cells was used, whilst for the World Climate data a search radius of 8 was used.
3. **Cell size and extent:** to ensure the raster outputs were continuous with the 30” resolution, the cell size was input at 0.0083333°. The extent used throughout the entire analysis was the administrative boundaries of Myanmar.

Monthly wind speed

The monthly average wind speeds were calculated with the newly interpolated datasets produced in the previous section. As both the monthly datasets were projected to the equal 30” resolution and interpolated to the identical administrative boundaries, the average was simply calculated using the average value of each corresponding cell within the two datasets. Each cell was also given an average value from the cumulative monthly averages obtained from the annual GWA dataset.

This average cell value provided the basis for the identification of the ratio of each month’s average wind speed against the cumulative average wind speed from each respective cell. As a result, the analysis was able to determine the three average wind speeds from each corresponding dataset and assign each cell with a monthly average wind speed value from the cumulative average of each dataset.

From the above processes, the produced result is effectively the long-term monthly average of daily total wind speed, for the time period 1960 – 2018. As such, the issue will seasonal
variability is addressed through the cumulative fifty-eight (58) years of historic wind measurements. Nonetheless, due to the unpredictability and continual variation in annual, monthly, daily and hourly wind speeds the results of this analysis may differ from real world measurements. However, as the aim of this analysis is to determine the theoretical potential of wind energy for the identification and preliminary assessment of the applicability of small scale wind installations for the electrification of rural and/or off grid communities, the values obtained in this method are of sufficient validity.

### Limiting factors and Applicability

As this analysis is focused on the identification of areas with the potential for small scale wind turbine installations, there is varying criteria used in this study which purely identifies the wind energy potential from small scale wind turbine installations.

For large scale wind installations, it is generally accepted the mean wind speed should be approximate six metres per second or higher (≥6 m/s$^{-1}$). Conversely, small scale wind installations only require an average wind speed of three metres per sec (3 m s$^{-1}$) or higher. There is some variation on the exact cut in speed required for energy production from small scale wind installation, with the general consensus being from two to six metres per second (2-6 m/s$^{-1}$) (Acosta, 2012; James & Bahaj, 2017). As a result, a limiting factor of three and half metres per section (3.5 m s$^{-1}$) was used in this study.

Furthermore, the limiting factors for the turbine was a two and a half (2.5) metre rotor radius and a maximum turbine height of thirty (30) metres. These factors were also a result of monetary requirements for installation, purchase and the possibility for villages to construct their own turbines.

General installation requirements of wind turbines, being a slope of less than twenty (20) percent and an installation area of no more than two and half (2.5) kilometres from the village locations was also employed to minimise distribution and the overall cost of the turbine installation.

Figure 12 identifies the exclusion areas from the details. It should be noted that most of the exclusion areas are as a result of high mountainous areas and the generally low wind speed in Myanmar.
Figure 12: Monthly Applicable Areas for Wind installation

Power generation potential

With the newly interpolated long-term monthly wind speed averages and the appropriate exclusion areas identified, the theoretical wind energy calculation was undertaken. For the purpose of the calculation the following formula was employed.

\[ P_{tp} = \frac{1}{2} \rho A v^3 C_p \] (3)

Where, \( P_{tp} \) is the theoretical power potential, \( \rho \) value is the constant air density value (1.225 kg/m\(^3\)) at 15°C at sea level, \( A \) is the rotor sweep area (19.63m\(^2\)). Wind speed is \( v^3 \) and provided for each 30″ cell. \( C_p \) refers to the power coefficient. As the maximum conversion of kinetic energy of a wind turbine is 59.3%, the power coefficient used in this study was 0.35 or 35%.

As such, the power generation of the entire Republic of Myanmar was completed. This allows for the continual use of the theoretical wind energy data should other organisations or individuals identify varied limiting factors than the ones used in this study.

For the purpose of this study, the theoretical wind energy data was filtered through the slope and location limitations mentioned above. For the purpose of the final analysis, regarding the applicability of hybrid energy systems, the average theoretical wind energy values were used for each respective village.
From the theoretical wind energy analysis, it is also possible to identify all applicable areas surrounding each respective village. As such, the analysis provides the opportunity for relevant stakeholders to have a preliminary assessment of the wind energy potential in multiple locations surrounding each village location.

4.4 Solar

The objective of this section was to determine the monthly energy potential of solar resources within Myanmar. As the focus of the study is primarily on the electrification of rural and currently off-grid communities, there is no assessment of potential large scale solar installations.

4.4.1 Solar Conditions & Assumptions

The aim of this methodology is not to define the processes and principles behind solar power but to provide the appropriate information to determine the community/village solar energy potential within Myanmar. As such, only Photovoltaic (PV) potential been used throughout this study.

This method focuses on cloud coverage as the main variable affected the solar potential of PV systems, as a result of the literature findings in the earlier section.

This method also utilises Global Horizontal Irradiation (GHI), Direct Normal Irradiation (DNI), and Global Tilted Irradiation (GHI) to determine the PV potential in Kilowatt hours per kilowatt peak (kWh/kWp).

In doing this, the results obtained can be easily scaled to provide solar energy capacity from a proposed installation capacity.

The solar potential temporal scale is months, with a spatial resolution of 30”. All data inputs, processes and results obtained through the analysis utilise the monthly time scale and 30” resolution.

4.4.2 Datasets

Satellite imagery

Satellite imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra and Aqua satellites and associated cloud mask were utilised in determining the monthly cloud coverage values. The daily cloud fraction values from the Terra and Aqua MODIS satellite provide a cloud mask which indicates whether a given area of the earth’s surface is obstructed by clouds or thick aerosols. The cloud mask is generated on a 250 and 1000-meter resolution and utilise various algorithms to differentiate values between various landscapes, with this study employing the 1000-meter, or approximately 30” resolution.

The cloud fraction and cloud mask values are updated daily and allow for the continual update of cloud coverage values, with the option of validation from historic data from 2002. An
extensive description of the processes and principles behind the Terra MODIS data and associated cloud mask is presented in Ackerman et al. (1997).

**Cloud coverage**

Also used were cloud coverage values produced by Wilson and Jetz (2016). The study developed high resolution 30″ global cloud climatologies from 15 years of MODIS archives of twice daily observations. These values were validated using the cloud observations collected form 5388 weather stations since 1971. The results from this study were primarily focused with identifying and predicting ecosystems and biodiversity distributions but were used in this study due to the corrections made from the MODIS data.

The study also improved on the MODIS data provided a seasonality variable which aims to assist in the calculation and rectification of seasonality variation. This was obtained through the twice daily and monthly cloud observations from the MODIS data values from the Terra and Aqua satellites from 2000-2014. The monthly average and twice daily averages across the time period from both satellites was used to determine the average variability on an inter-annual and intra-annual scale (Wilson & Jetz, 2016).

Validation of cloud frequency was also performed in the study by incorporating global observational datasets of synoptic weather reports collects at 5388 weather station from 1971-2009. The reports from the weather stations were compared with the MODIS data from the Terra and Aqua Satellites and was found to capture 78% of the variability in monthly mean cloud data (Wilson & Jetz, 2016).

Therefore, the cloud frequency values obtained from the study by Wilson and Jetz (2016) are used as the basis to account for and limit the effect of seasonality in cloud coverage for the basis of PV solar potential capacity.

**SolarGIS Photovoltaic potential**

The photovoltaic (PV) potential of Myanmar has previously been produced by Suri et al. (2017) as a part of World Bank group initiative. As the data in the report is open source and the values are of a monthly high resolution (30″), the provided PV values form the basis of this study’s assessment of Myanmar’s solar energy potential. The study aimed to improve the awareness and knowledge around solar energy technologies to identify and evaluate the most feasible areas for the implementation of solar energy technologies.

The photovoltaic potential provided from the Suri et al, (2017) study was based on various satellite-based models and meteorological measured and validated values. The satellite-based models calculated solar irradiance by determining clear sky irradiance, with all atmospheric effects except clouds. Cloud properties were integrated with the clear sky irradiance to determine GHI, DNI and GTI. These values were then assessed against meteorological measurements from both synoptic weather stations and satellite observations. An extensive description of the methodology used to generate the solar variables is presented in the above-mentioned study.
For the scope of this research it is important to note that the values utilised from the Suri et al. (2017) study are 30″ long-term (1999-2015) monthly daily total average of potential photovoltaic electricity production (PVOUT) in kWh/kWp. The technical parameters of the study are described in Table 3.

Table 3: SolarGIS Technical Parameters (Suri et al., 2017)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal capacity</td>
<td>Configuration represents a typical PV power plant of 1 MW-peak or higher. All calculations are scaled to 1 kWp, so that they can be easily multiplied for any installed capacity.</td>
</tr>
<tr>
<td>Modules</td>
<td>Crystalline silicon modules with positive power tolerance. NOCT 46°C and temperature coefficient of the Pmax -0.45%/K</td>
</tr>
<tr>
<td>Inverters</td>
<td>Central inverter with Euro efficiency 97.5%</td>
</tr>
<tr>
<td>Mounting of PV modules</td>
<td>Fixed mounting structures facing South with optimum tilt (the range from 12° to 30°). Relative row spacing 2.5 (ratio of absolute spacing and table width)</td>
</tr>
<tr>
<td>Transformer</td>
<td>Medium voltage power transformer</td>
</tr>
</tbody>
</table>

4.4.3 Processes and Calculations

Cloud Coverage

The average monthly cloud coverage was generated from the daily values obtained from the Terra and Aqua MODIS values and the monthly cloud coverage data from the Wilson and Jetz (2016) study. The benefit of generating an average cloud coverage value, from these three sources, is the ability to account for the seasonality and variations within an annual and inter annual scale. The addition of the continually updating cloud datasets from the MODIS satellites, couples with the methodology from the Wilson and Jetz (2016) allows for the continual update of the cloud coverage values within the CORE-app. Also, the average of both data sets allows the artefacts and shortcomings of the results obtained from the MODIS satellites to be rectified.

As the data sets were the same resolution, the integration of the two data sets can be easily obtained through the use of the raster calculation tool in the Quantum GIS software. For the areas within the MODIS data sets which have no-data, these areas were filled using the r.fillnull function which interpolates the surrounding cells and provides a value to these no-data areas. As the cloud coverage datasets have a high resolution the interpolation of no-data cells is appropriate as once the no data cell is provided a value from its surrounding values, this value is then integrated with its corresponding value provided in the study by Wilson and Jetz (2016).
Figure 13: Monthly Cloud Coverage Average (data from Wilson and Jetz (2016) and Satellite Data)
SolarGIS Photovoltaic potential

As the photovoltaic potential values are already provided from the Suri et al., (2017) study, these values were merely accepted as being appropriate for this study. The cloud coverage data will be included in the CORE-App datasets for future solar analysis or the assessment of applicable solar resource databases when they become available.

![SolarGIS Monthly PV Potential (data from Suri et al., 2017)](image)

Figure 14: SolarGIS Monthly PV Potential (data from Suri et al., 2017).
Limiting factors

For the basis of the assessment of solar energy potential there are various limiting factors which were included in the analysis.

As the solar PV potential is displayed in kWh/kWp, an assumption of a 50kW solar installation was assumed for the community renewable energy potential assessment. The original data is available in its current scale for the suitability and preliminary profiling of solar PV installations.

Furthermore, it is generally accepted that a solar PV installation should not be undertaken on a slope of greater than 10 degrees. As such, this limitation has been included in this study. Figure 15 illustrates the suitable areas where solar PV installations can be undertaken.

Figure 15: Applicable Areas for Solar PV installation
4.5 Hydropower

Myanmar’s theoretical hydropower energy potential was determined through the use of global runoff models, digital elevation models and several processes detailed in the study by Hoes et al (2017). The aim of the analysis is to identify the potential hydropower capacity of villages throughout Myanmar.

4.5.1 Hydrological conditions and assumptions

The main objective of the hydropower analysis is to determine the theoretical energy potential of Myanmar’s hydropower resources. This analyse aims to identify suitable areas for the implementation of small scale hydropower installation for the purpose of providing electricity for rural and/or off grid communities within Myanmar.

As the focus is on hydropower potential, this analysis focuses on identifying Myanmar’s river networks, discharge (m$^3$ s$^{-1}$) and head values (m). From these parameters the study has been able to calculate the theoretic hydropower potential of all applicable river networks within Myanmar.

Runoff was the only hydrological variable utilised in this analysis. The PCR-GlobWC runoff model used in this analysis accounts for water usage (irrigation, domestic, industry and livestock), water exchange (infiltration, capillary rise, and percolation), as well as atmospheric conditions (rainfall, evaporation, and snow melt).

The spatial scale employed in this analysis is 3” resolution, with a temporal scale of the monthly average of daily totals, from the period 1971-2005.

There are several hydrological assumptions which were made prior to the hydropower analysis. One such assumption is the ‘steepest slope principle’ used in the runoff model. Due to the low resolution of the runoff model all cells runoff flow into the steepest neighbouring cell, meaning there is no separation of flow with the runoff models cell. This issue was rectified when the model was projected over a three (3) arc second resolution, which was used throughout the hydropower analysis.

This analysis does not aim to predict the exact hydropower potential of river networks within Myanmar, but to identify suitable areas for hydropower installations and preliminary results on the potential hydropower capacity for the electrification of rural and off-grid communities throughout Myanmar.

4.5.2 Datasets

Global runoff model

The global runoff model used throughout this analysis was a simulated runoff model title PCR-GlobWC presented by the Inter-Sectoral Impact Intercomparison Project (ISI-MIP). The runoff model provided long-term monthly average overland runoff flow as a product of simulated water exchange, water using and atmospheric conditions, for the period 1971-2005. The runoff model has a relatively low resolution of 30’, or 0.5 degrees, and was
resampled to a 3” resolution later for the purpose of this study. The principles and processes of how the global runoff model was generated and the input data sets is extensively detailed in the article by Wada et al. (2014).

Even so, there exists issues with the runoff model which can result in a strong variation from real world measurements. This was highlighted in the article by Wada et al. (2014), who identified the water balance from the model and field measurements was slightly overestimated in Asia. For the scope of this research, these issues are of little significance as this analysis aims to identify preliminary results on the potential hydropower capacity Myanmar.

**Digital Elevation Model**

The Digital Elevation Model (DEM) employed in this analysis was obtained from the HydroSHEDS (Hydrological data and maps based on Shuttle Elevation Derivations at multiple Scales) (Lehner, Verdin and Jarvis, 2006). HydroSHEDS elevation model is derived from elevation data which was collected as part of the Shuttle Radar Topography Mission (SRTM). This information is then integrated with SRTM water body data, various SRTM databases, vectorised river network data, and other elevation models to produce high resolution topographical maps for hydrological assessment purposes (Lehner, Verdin and Jarvis, 2006). DEM sets are available are varying resolutions, with the highest resolution, 3” being used in this analysis.

HydroSHEDS technical documentation (Lehner, Verdin and Jarvis, 2006) addressing the hydrologic conditioning of the digital elevation models in extensive detail. In reference to this study, the analysis of the conditioning methods of elevation models is not significant, however the conditioning modification are broadly discussed below;

- Deepening of open water sources, to ensure derived flow stays within these sources.
- Weeding of coast zones, removes of artefacts which cause backflow effects from oceans.
- Stream burning, enforces known river courses and inputs them directly onto the DEM.
- Filtering, removal of spikes and wells to preserve and enforce continued river flow and low elevation areas.
- Moulding of valley courses, removal of small obstacles to improve river delineation in tropical lowland areas.
- Sink filling, to ensure only natural sinks are included in the DEM.
- Carving through barriers, removal of obstacles when river network is known.
- Manual modelling, manual modification of DEM when river network is known to be incorrect or incomplete.
In Figure 16 the three (3) arc second DEM of Myanmar’s administrative areas is presented.

Figure 16: Myanmar 3" DEM (HydroSHEDS) (data from Lehner, Verdin and Jarvis, 2006)
4.5.3 Processes and Calculations

Resampling runoff and interpolation

To estimate the discharge of river networks within Myanmar, the global runoff model needed to be resampled from the 30’ to the desired 3” resolution. Prior to the resampling, the average monthly runoff from the global runoff model was required.

The model was separated into the long-term monthly runoff average as a result of the cumulative annual average and values from values from each respective month across the simulated thirty-four (34) year time period, 1971 – 2005.

As the long-term monthly runoff data was displayed in kilograms per metre per second (kg m$^2$ s$^{-1}$), the values needed to be converted to cubic metres per second ($m^3 s^{-1}$). To undertake this conversion, the following equation was used.

$$R(m^3 s^{-1}) = (Qh * A) * 1000$$ (4)

Where, $R(m^3 s^{-1})$ is the monthly average runoff per cell. $Qh$ is the average monthly runoff. $A$ is the total area of Myanmar ($m^2$).

The above calculation provided a monthly average runoff value for each cell in cubic metres per second ($m^3/s$). The area used for this calculate was all areas falling within the latitude of 90-105 degrees East and longitude of 10 – 30 degrees north. This was done to ensure the interpolation considered the runoff from varying areas outside the administrative boundaries of Myanmar.

Due the new runoff model results having a resolution of 30” and the DEM having a resolution of 3”, the runoff data was resampled to be consistent with the DEM. To do this, each cell within the above runoff model dataset was assigned the value of its middle point.

The IDW interpolation in the SAGA package of QGIS was used as per the details in section 1.3.3 of this study. For the purpose of the runoff resampling the following parameters were used:

1. **Inverse distance Power (P):** The value used in this instance is 2.
2. **Search Radius:** A global search radius of 100 was selected.
3. **Cell size and extent:** to ensure the raster outputs were continuous with the three (3) arc second resolution, the cell size was input at 0.00083333°. The extent used was the extent of the calculated monthly runoff average.

The interpolation considered areas of ocean with the interpolated average runoff values given to these cells. These oceans cells were not considered in the discharge calculation and were merely to allow for interpolation of coastal areas and surrounding islands. As such, the
values for Myanmar’s islands may be significantly different from measured results. Nonetheless, with the addition of measured runoff values the methodology could still be used to determine the hydropower potential of these islands.

**Cell size and runoff**

With the interpolation and resampling of the global runoff model, the cell size and runoff per cell can be calculated with Equation 5.

\[
R_{\text{per cell}} = \left( \frac{R(m^3s^{-1})}{1000} \right) \times \left( \frac{\text{as}}{\text{degree}} \right) \times \left( \frac{\text{as}}{\cos \left( \frac{\text{latitude} \times \pi}{180} \right)} \right) \times \left( \frac{\text{m}}{\text{degree}} \right)
\]  

(5)

Where, \(\frac{R(m^3s^{-1})}{1000}\) is monthly average runoff per cell. \(\text{as} \) is the arc second value of 0.00083333. \(\text{latitude}\) is the average latitude of Myanmar (22.00°N). \(\frac{\text{m}}{\text{degree}}\) is the metres per degree latitude with the distance at 22.00°N =108262m.

As the average latitude was used for this calculation, the cell size and length would vary slightly in the northern and southern Myanmar. Although unfavourable, there is no real significant issue as the analysis is only considering a variation of nineteen degrees (19°). This issue is also set to be address in the subsequent stages of the CORE-App analysis.

**Flow accumulation and Discharge**

In order to determine cell discharge and flow accumulation the r. watershed water basin analysis program was used in the GRASS package of QGIS.

The r.watershed program generates a series of maps indicating the following attributes:

- **Flow accumulation**, the absolute value of overland flow that crosses each cell. This attribute also provides the river network map as it only visualises cells which flow into other cells or sinks.
- **Topographical index**, the tendency for water to accumulate at any given point in the catchment and the tendency for the water to flow downstream.
- **Stream power index**, the power of water flow at any point in the catchment and the gravitational tendency to move.
- **Drainage direction** contains the drainage direction and degrees that surface runoff will drain from each respective cell.
- **Basin map** creates unique basin ids depending on the cells which form that particular basin.
- **Stream segments** contain stream segments which correspond to the basin ids.
- **Length slope (LS) and slope steepness (SS)**, factors generated for the Universal Soil Loss Equation.

The full process and principles behind the generation of the above attributed can be viewed in detail through the GRASS r.watershed manual. For this study, the input values needed to generate the above attributes are detailed as follows:
• **Elevation:** three (3) arc second DEM as presented in Figure 16.

• **Overland flow (Q):** monthly raster dataset defined in section 1.5.2.4.

• **Minimum size of exterior watershed basin:** defines the minimum size of watersheds basins in cells. In the scope of this study, a value of 5000, equivalent to approximately 50 km², was used.

• **Maximum length of surface flow:** identifies the maximum length of overland flow in metres. For this study a value of 2 000 000 was used, approximately 200 km.

• **Positive flow accumulation:** was checked to correct likely underestimates

• **Extent and Resolution:** Extent was defined as the administrative boundaries (Figure 6) and resolution value was 0.00083333°, approximately 3”.

Subsequently, the above attributes were generated for each month, though only the flow accumulation (Q) and river networks were used in the further analysis. As this study is preliminary assessment of hydropower resources, the remaining attributes were archived for later investigation and validation of field measurements in the next stages of the CORE-app process.

**Slope and Head calculations**

From the r.watershed program, the monthly river network can be visualised through the flow accumulation output. As the flow accumulation utilises the DEM and global runoff model, the river network is able to be effectively visualised, with even the water flowing around obstacle being observed.

In order to determine slope and head, the river network must first be filtered to only include those cells which are certainly river cells. To do this, the minimum monthly discharge of three cubic metres per sec (3 m³ s⁻¹), with the following equation used in the QGIS raster calculator. The minimum discharge value was chosen as a way of limiting the inclusion of small streams which would not be suitable for hydropower installations.

\[
\left(\text{"monthly discharge"} < 3 \right) \times 0 + \left(\text{"monthly discharge"} \geq 3 \right) \times \text{"monthly discharge"}
\]

\[
\left(\text{"monthly discharge"} < 3 \right) \times 0 + \left(\text{"monthly discharge"} \geq 3 \right) \times 1
\]

(6)

These equations ensured that cells with a discharge smaller than the minimum three cubic metres per sec (3 m³ s⁻¹) are assigned a 0 value, and cells equal or larger assigned the original discharge values or a 1 value, respectively. For each month the 0 value cells were assigned a no data value through the transparency section of the raster layer properties in QGIS.

To determine slope, the resulting data from equation 6 was used to mask the DEM, resulting in the elevation of the river networks with a discharge greater than the three cubic metres per sec (3 m³ s⁻¹) criteria. The slope of this resulting river network elevation was determined using the GDAL slope calculation tool. For this tool the value of ratio of vertical to horizontal units was input at 108262, representing a cell size of approximately 86.04 m, at a latitude of 22° North.
The resulting slope data and cell size were required to determine the head values of each cell within the length of the river networks. As the head available for hydropower will be significantly less than the potential head due to head reduction from structural configurations and friction, the following conservative head values were determined from the following (Hoes et al., 2017):

\[ \text{Head} = \text{slope} \times 2 \times \text{cellsize} \]  

(7)

For the purpose of hydropower potential analysis, the head values from the cumulative applicable river networks across the wet season months, being June – August, were used in the theoretical hydropower calculation. These values were chosen due to the inclusion of all streams which met the minimum discharge requirements throughout the year.

For the purpose of this study, the above head values were calculated using the cumulative sum of the all values within three upstream cells of each cell based on the generated drainage direction produced in section 1.5.2.5. In the event, the cell was the start of an applicable area, the calculation would begin from that cell and continue in drainage direction of that cell. As such, the head values from cell was a product of the drainage direction and associated elevation.

As the future stages of the CORE-App will focus on three varying in stream river technologies, the use of this cumulative head value allows for the appropriate assumption of head along 300 m intervals.

**Hydropower potential**

In the scope of this study, the general formula for hydropower potential was applied:

\[ H(\text{kW}) = n(\%) \times g(m \text{ s}^{-1}) \times Q(m^3 \text{ s}^{-1}) \times f(\%) \times \Delta H(m) \]  

(8)

Where, \( n(\%) \) is the turbine efficiency, with a value of 0.7 or 70% used in this analysis.\( g(m \text{ s}^{-1}) \) is the gravity constant of 9.81 m s\(^{-1}\).\( Q(m^3 \text{ s}^{-1}) \) refers to each particular cells discharge.\( \Delta H \) is the head values from the wet season river networks mentioned above.\( f(\%) \) refers to the amount of discharge used for the calculation. A value of 15% was used to ensure environmental flow requirement and other water usage requirements.

The resulting raster datasets provide the monthly hydropower potential for the river networks which meet the minimum discharge and maximum head thresholds.

In the scope of this study, these results were used to estimate the community renewable energy potential and the potential for the implementation of hybrid mini grid systems.
4.6 Estimation of Community Hybrid Renewable Energy Potential

As stated, the first stage of the CORE-App is to provide a preliminary assessment of the renewable energy potential for every village in Myanmar. From the above methodology, this study is able to provide a preliminary monthly renewable energy potential, for wind, solar and hydropower resources. As biomass could only be produced on an annual 5’ resolution, it was excluded from this stage of the study.

From this methodology it is possible to identify areas which have limited and seasonal potential, providing the possibility to identify niche opportunities in exploiting renewable energy sources which may have been overlook due to their intermittent tendencies.

For the scope of this study the following provinces have been selected for further analysis based on their rural status and large proportion of village:

- **Lashio Province, Shan State**
  Encompasses 760 villages, located on a low mountain range close in north-eastern Myanmar.

- **Kayaing Province, Chin state**
  Encompasses 838 villages, located in a high mountainous area in North-western Myanmar.

![Figure 17: Location of Villages for Community Renewable Energy Profiling](image)
4.6.1 Assessment Conditions and assumptions

For the purpose of the analysis of the above provinces there has been several assumptions and conditions employed.

Wind

The follow assumptions were employed for potential wind resources:

- **Turbine**: potential wind estimates were made using the turbine specifications detailed section 4.3.1.
- **Location**: only areas within 2.5km of each village were included.
- **Value**: the mean value of all applicable areas surrounding each respective village were used.

Solar

The following assumptions were made for potential solar resources:

- **50 kW installation**: as the PV values are displayed in kWh/kWp, the assumption of a 50kW solar installation was made.
- **Location**: only applicable areas within 1km of each village were included.
- **Value**: the mean value of all applicable areas surrounding each respective village were included.

Hydropower

The following assumptions were made for potential hydropower resources:

- **Hydro assumptions**: assumptions made in the hydropower analysis section affect this analysis and can be viewed above.
- **Location**: locations within 2.5 km of each village were included.
- **Value**: the average minimum value was used for this assessment. As there is a high variability in hydropower potential, due to the seasonal variations in discharge, the minimum value provides a conservative hydropower estimate for each village.

4.6.2 Processes and calculations

The community renewable energy potential analysis was undertaken using the open source programming platform R. The script for the assessment can be viewed in more detail in Appendix 1.

The assessment applied the above assumptions to generate the monthly renewable energy potential profiles. The resulting profiles are able to be directly uploaded to a designated web page and will be accessible, with an open license for the codes and processes used. Furthermore, with the continual update and validation of current renewable potential results, the energy profiles will be constantly updated to provide the most appropriate information.
Also, the next stages of the CORE-App process involve the demand profiling of every village within Myanmar. As such, in the later stages of the CORE-App the renewable energy potential and current demand profiling will be accessible and assist in the identification and preliminary site assessment of potential hybrid mini grid systems.
5 Results & Discussion

5.1 Biomass

As observed in Figures 18 & 19, there exists significant energy potential from Sugarcane residues. From the findings it appears that a considerable energy potential exists in the delta region and many areas at the base of mountainous areas, with much of the eastern and northern areas having significant energy potential from both residues.

Form the density plot (Figure 20), it is observed that both sugarcane tops and bagasse’s have approximately the same theoretical annual energy potential. The significant energy potential of both residues may be the result of the relatively low energy use factor and subsequent high surplus availability factor for both the residues. This low usage of residues coupled with the high sugarcane production per hectare illustrates the abundant energy potential of sugarcane residue.

![Sugarcane Residue Annual Energy Potential](image)

*Figure 18: Sugarcane Residue - Annual Energy Potential*
Figures 20 & 21 identify the varying potential of maize residues throughout Myanmar. As shown, the annual energy potential of maize cob, husk and stalk vary significantly throughout the country, with maize cob having a significantly higher potential energy value than the other residues. This is further illustrated in Figure 21, where it can be understood that the kWh ha\(^{-1}\) for maize cob is constantly higher than both maize husk and maize stalk in majority of the cultivated areas.

It is interesting to note, that in the southern regions of Myanmar there appears to be a high disparity in energy potential throughout the three residues. This may be a result of the surplus availability factor and the hectares cultivated for the crop, with maize husk being a predominate residue type accounting for the higher energy potential in areas with less cultivated hectares of maize.

As maize is an extensively cultivated crop through Myanmar, it appears there is significant energy potential from all three residue types identified. However, as much of the crop residue usage and surplus availability factors vary significantly, there is a greater potential for currently underutilised maize cob and stalk residues.
Figure 20: Maize Residue - Annual Energy Potential

Figure 21: Maize Residue Density Plots
From Figure 22 & 23, it can be observed that the annual energy potential of rice residues is quite low, with only areas the eastern and northern of the country having significant theoretical energy potential. Both rice straw and rice husk appear to have relatively similar energy potential throughout the country. Both residues also have relatively similar energy profiles in terms of density, with over 60% of all areas having a log10 kWh ha\(^{-1}\) of less than 2.

The low energy potential of rice residues could be attributed to the high portion of the residues currently utilised for energy use, whether cooking or lighting. As a result, although the crop is highly cultivated within the country there may be relatively low amounts of residue surplus due to the high usage and as such lower potential due to lack of biomass materials.

*Figure 22: Rice Residues - Annual Energy Potential*
From the analysis of biomass residues, it can be observed that much of the residues have significant annual energy potential. Although there is some variation between the crops and the subsequent residues produced from each crop, it would be sufficient to state there exists a significant potential for biomass throughout the country.

From this analysis it was also seen that due to the varying potentials in each crop residue there may be a case for diversifying biomass energy contributions, with varying crops being utilised throughout the year. As each of the crops in this study have differing planting, harvesting, residue production and energy use factors it may be beneficial to determine how the availability and associated energy production from biomass residues changes throughout the year. The resulting information could better understand the biomass energy potential of various cultivated crops and provide a basis for the theoretical calculation of energy potential of varying crop types.

Furthermore, through the input of additional cultivated crops and the continual exclusion of crops grown exclusively for energy production, it is possible to determine the energy potential of residues without impacting on food security.
5.2 Wind

The wind energy potential under the suitability constraints is detailed in Figure 25, with Figure 24 detailing the average daily wind speed of each respective month. The potential for wind energy appears to be most substantial from April to July. Although there appears to be limited areas with wind energy potential, the applicable areas generally have significant potential during the early wet season months. With potential values of 60 kWh per day and higher, the wet season months provide a significant potential for power generation through the implementation of small scale wind turbines.

Much of the wind energy potential is situated throughout the central dry zone, with these areas providing the opportune location for wind installations. This can be attributed to the high wind speeds observed throughout these regions during the wet season months. Figure 24 supports this assumption, with much of the country having significantly low monthly wind speeds during the dry season months (< 4 m/s), with wind speed often exceeding 5 m/s during the wet season months.

Furthermore, with the suitability constraints defined in Figure 12, much of Myanmar’s mountainous areas, and areas with low speeds were excluded from the analysis. As such, many of the suitable areas for small scale wind installations are located in the central dry zone, coastal and areas at the base of mountainous terrain.

![Figure 24: Average Monthly Wind Speed (m/s)]
The distribution of the wind energy potential under the suitability constraints can be observed in more detail in Figures 26 and 27. Figure 27, details the distribution of wind energy potential and clearly illustrates the growing potential from April to September. The figures also identify that many of the applicable areas constantly fall under a theoretical potential of < 100 kWh/day, suggesting there is a large seasonality significance of wind energy within the country.

Nonetheless during the observed peak energy times, being April to September, the potential energy can increase by almost 100%. This suggests that although the reliability of wind energy is inconsistent, there are significantly times that small scale wind installations would be advantageous for energy production. This seasonality aspect of wind energy throughout the country supports the idea of the establishment of multiple renewable resources decentralised energy systems for the purpose of rural electrification.
Figure 26: Monthly Distribution of Wind Energy Potential

Figure 27: Potential Wind Energy Density Plot
5.3 Solar

Solar energy potential determined under the suitability constraints is detailed in Figure 28. From this, it is observed that Myanmar has relatively significant solar energy potential throughout the year, with much of the energy potential occurring during the dry season months of November to April. Figure 29 demonstrates that from November to April, the applicable areas identified in Figure 15, have a potential of > 100 kWh/day.

Although there is significantly high solar potential, during the wet season months (May – October), the potential energy generation from a 50kW solar installation falls to well below 100 kWh/day. This trend is also identified in Figures 29 and 30, which illustrate the reduction in energy potential during the months of May to October and the subsequent increase of energy potential during the months of November to April. This observed reduction in energy potential during the wet season months can be observed to be approximately half of the potential observed during the peak periods.

Although there are substantial variations in solar energy potential throughout the year, the results of this analysis suggest there remains significant energy potential year-round. Furthermore, the seasonality of solar resources throughout the country supports the idea of the establishment of multiple renewable resources decentralised energy systems for the purpose of rural electrification.

![Theoretical Solar Energy Potential (daily kWh/kWp)](image)

*Figure 28: Solar Energy Potential under suitability constraints (daily kWh/kWp)*
Figure 29: Monthly Distribution of Solar Energy Potential

Figure 30: Potential Solar Energy Density Plot
5.4 Hydropower

As mentioned, Myanmar has a significant hydropower potential due to the vaster hydrological resources that exist within the country. As observed in Figure 31, the Lashio province has extensive river networks which meet the suitability constraints defined in section 4.5.

The Lashio province also appears to have significant hydropower potential throughout the year, with the potential increasing during and subsequent to the wet season (Figure 32). From July to November, the hydropower potential in the region is seen to increase with much of the distribution of hydropower potential moving towards a higher energy potential prior to a decrease in the dry season.

It is also interesting to note, the hydropower potential that exists within the Lashio region heavily varies in its potential, with a large distribution of potentials observed in Figure 32. This varied hydropower potential is primarily due to the differing size of river networks that exist with the area and the respective potential from each river network section.

The continued significant potential of hydropower within the Lashio province is identified in Figure 33. From this, it can be observed that the hydropower potential within the region remains relatively steady, with the mentioned increases during the wet season months. As such, it can be shown that from this study there is a significant potential of hydropower resources within the Lashio province.

Figure 31: Lashio Province River Network under constraints
Figure 32: Lashio Province Hydropower Potential under suitability constraints (kWh/day)

Figure 33: Lashio Province - Hydropower potential density plot
The Kayaing province has extensive hydrological resources, with Figure 34 identifying the expansive river network which meet the suitability constraints defined in section 4.5. As expected from this extensive applicable river networks, the Kayaing province has significant hydropower potential throughout the year.

As observed in Figure 35, the Kayaing regions hydropower potential remains significant throughout the year with a magnitude increase during the months of July to December. This increase amounts to an approximate 10-fold increase in hydropower potential throughout the region during the wet season months, prior to the same magnitude drop in potential for the remaining months.

Figure 35 identifies the increase of hydropower potential during the wet season months and further identifies the continued high energy potential during the year. It is interesting to note, that this continued significant hydropower potential identifies the Kayaing province as a prime location for further hydropower studies.

From this study, it can be stated that the Kayaing province appears to have annual significant hydropower potential with a substantial increase during the wet season months. This hydropower potential could be attributed to the high head values observed in the area and the significant hydrological conditions observed through the analysis of hydropower potential.

Figure 34: Kayaing Province River Network under constraints
Figure 35: Kayaing Province Hydropower Potential under suitability constraints (kWh/day)

Figure 36: Kayaing Province - Hydropower potential density plot
5.5 Village profiling

From the methodology identified in section 4, it was possible to determine the preliminary renewable energy potential for all villages identified in Figure 18. To visualise these findings, four villages from each of the provinces, Lashio and Kayaing, are detailed below. The villages were selected at random from different areas within each respective province to assess the profiling and identify the spatial and temporal variations of resources within the provinces. The interface for the village renewable energy profiling is detailed in Appendix 2. As mentioned, the profiling is generated using HTML format and therefore can be directly placed onto an applicable webpage. Additionally, as the village profiling is presented in logarithmic scale, the potential of each resource is only shown when the potential exists, clearly identifying the variability and seasonality of each resource.

From the Lashio province, the following four villages daily renewable energy potential profiles are presented:

- Ton Hpa Lant (Figure 37);
- Kone Nyaung (Figure 38);
- Nawng Sang (Figure 39); and
- Man Sant (Figure 40).

The profiles of each of the above villages show the relatively consistent and continually high solar potential, with a slight drop in potential during the wet season months of April – August. This continuous solar potential suggests that the Lashio province has generally high solar potential throughout the year, supporting the establishment of PV solar energy systems within the area.

Wind potential throughout the four Lashio villages varies significantly on both a monthly and village level. Generally, there appears to be significant variation in the monthly wind potential throughout the year, with the only exception being the fairly consistent values observed in Ton Hpa Lant. Both Nawng Sang and Kone Nyaung have wind potential from January to September, with the potential disappearing in the end of the year. Man Sant has the least potential for wind energy with approximately 7 months of wind energy generation potential. As such, it can already be seen that the wind installations may not be applicable to all villages within the Lashio Province, with each installations energy potential varying significantly.

The hydropower potential of the four villages also varies drastically between the villages and on a monthly scale. For example, Nawng Sang has substantial potential throughout the year, with a notable increase during the wet season months. Alternatively, Ton Hpa Lant had no observed hydropower potential, while Man Sant and Kone Nyaung only has hydropower potential during and immediately after the wet season (June – December).

As a result of the village profiling it can be observed that each of the abovementioned villages can obtain energy from varying renewable resources. Ton Hpa Lant can potentially utilise solar and wind resources, while Nawng Sang, can utilise predominately solar and hydro resources, with the ability of wind resources to supplement their energy needs. Man Sant and Kone Nyaung have the potential to develop solar PV systems, with wind resources...
from January to July after which hydro resources can be used to combat the decrease in wind energy during the second half of the year and wet season occurrence.

Figure 37: Ton Hpa Lant Village - Daily Renewable Energy Potential. Please note: y-axis is given in log10 scale.

Figure 38: Kone Nyaung Village - Daily Renewable Energy Potential Please note: y-axis is given in log10 scale.
Figure 39: Nawng Sang Village - Daily Renewable Energy Potential Please note: y-axis is given in log10 scale.

Figure 40: Man Sant Village - Daily Renewable Energy Potential Please note: y-axis is given in log10 scale.
From the Kayaing province, the following four village were selected at random from varying locations within the Kayaing province and each respective daily renewable energy potential profiles are presented below:

- Saik Har (Figure 41);
- Kin Kan Kone (Figure 42);
- Shar Tai Lai (Figure 43); and
- Darl Sone (Figure 44).

As seen in the Lashio province, the solar energy potential of the four villages in the Kayaing province is significant and comparatively constant throughout the year, with a small decrease in potential during the wet season months suggesting the entire Kayaing province has constant high solar energy potential.

Wind energy potential was also seen to vary drastically both throughout the villages and temporally. Saik Har and Kin Kan Hone have potential similar to that of solar resources from January to June, with a substantial decrease after June. Shar Ta Lai’s wind energy potential follows this pattern, however with smaller overall potential, whilst Darl Sone only has wind potential during the first half of the year, with decreasing and eventually zero potential during August.

The potential energy generation from hydropower resources also varies both on a village and temporal scale. For instance, both Saik Har and Darl Sone have high hydropower potential overall, with a slight decrease in the first quarter of the year and a subsequent increase from April-May. Shar Ta Lai has a varied hydropower potential throughout the year with no potential prior to a sharp increase of hydropower potential in May. Kin Kan Kone has the most variable hydro potential, with a sharp increase from May followed by a sharp decrease from October to no potential in December and January.

Similarly, to the observation made in the village profiling of four villages within the Lashio Province, it can be seen that each village can hypothetically obtain energy from a mixture of renewable energy resources. As such, Saik Har, could utilise all three renewable resources, with hydro and solar being the two predominately used while the wind resources could be employed to provide electricity to productive end uses. Kin Kan Kone has the potential to utilise both wind and solar, with hydro resources being used at peak times to balance the reduction in wind resources. Shar Ta Lai has the possibility to utilise all three resources, however wind and solar are the most consistent, with hydropower being accessible for approximately 8 months throughout the year. Darl Sone has the highest potential in hydro and solar, with wind resources available during January – August.

As seen from the village profiling, there is a temporal and spatial variation in the renewable resource potential of each village. As discussed, each village has an observable optimal mix of resources, with the decrease and increase of each respective resource allowing the balance of potential energy throughout the year. Also, as hydropower was observed to have the most significant potential, it can be argued that these villages may not see the benefit of hybrid renewable energy systems and select only hydropower resources for their electrification needs. Alternatively, the high hydropower potential could allow for the establishment of poly centric decentralised grid networks effectively connecting various villages by a renewable mini-grid system.
Figure 41: Saik Har Village - Daily Renewable Energy Potential Please note: y-axis is given in log10 scale.

Figure 42: Kin Kan Kone Village - Daily Renewable Energy Potential Please note: y-axis is given in log10 scale.
Figure 43: Shar Ta Lai Village - Daily Renewable Energy Potential Please note: y-axis is given in log10 scale.

Figure 44: Darl Sone Village - Daily Renewable Energy Potential Please note: y-axis is given in log10 scale.
6 Discussion

This study aimed to identify the renewable energy potential of biomass, solar, wind and hydropower resources on a 30” spatial and monthly temporal resolution. From the study, biomass energy potential was merely able to be produced on a 5’ spatial and annual resolution. Alternatively, solar, wind and hydropower were able to be modelled at the intended 30” spatial and monthly temporal resolution.

From the results of the study, it can be determined that biomass has an extensive energy potential from the three crop types measured, with the variation of agricultural residues from the selected crop types having diverse energy potentials. Although the biomass analysis could only produce an annual potential, the methodology incorporated allows for the development of an infield field calculator which can provide a more comprehensive analysis of an areas biomass potential.

Solar, wind and hydropower resources were able to be modelled on the desired spatial and temporal resolutions. As a result, the village profiling of both the Lashio and Kayaing provinces could be undertaken. The results of this profiling identify not just each resources potential, but the applicability of hybrid energy systems, allowing the seasonality and subsequent fluctuation of each resources energy potentials to be observed.

As this is the first study for the CORE-app, it acts as the preliminary assessment of energy potential to be continually developed in future stages of the applications process. Additionally, as this study provides the methodology and utilises entirely open source data and software, there is the possibility for similar assessments to be undertaken on other regions or countries of interest.

The results of this study will greatly support the current development of the CORE-app, by providing the preliminary resource potential assessment and be an early tool for renewable energy practitioners to understand the varying energy potential of each respective village within Myanmar.

6.1 Comparison to existing knowledge

The results of this study consolidate the knowledge that Myanmar has extensive renewable energy resources which can be utilised for rural electrification (Kyaw et al., 2011, Sovacool, 2013, and Sasaki et al., 2014) Although the results support the observations in existing knowledge, the use of a high spatial and month temporal resolution allows for a more comprehensive analysis of renewable energy potential. The ability to determine a monthly resource potential for each respective village and resource type.

As such, this study provides a more comprehensive observation into the seasonal, spatial and temporal variation in resource potentials for each village community in Myanmar, with many of the other applications focusing on annual, or regionalised energy potentials. For example, the IRENA Global Atlas for Renewable Energy primarily focuses on the annual potential of wind and solar resources on a world-wide scale (IRENA, 2017). Furthermore, although there are functions to determine temporal variations, the application does not provide a monthly
potential for wind and solar resources, with hydropower and biomass potentials currently being developed with another tool, which will not be linked to the current application.

Additionally, other applications focus on only one resource potential or localised regions. As defined in the section 4 of this study, the solar study by Suri et al., (2017) focused on solar power, while the study by Ener and Devel (2015) focused on the annual theoretical potential of solar, wind and biomass.

As such, it can be stated that the combination of all four renewable resources, coupled with the high spatial and monthly temporal resolution, allows the CORE-app and the results of this study to provide more comprehensive observations into the renewable energy potential of villages within Myanmar.

Moreover, although the results of this study support the idea of high renewable resource potential for the purpose of rural electrification, the methods undertaken offer a new methodology in determining the village specific resource potential for the development of decentralised renewable hybrid energy systems, not just for Myanmar but an areas or regions of interest.

6.2 Potential to support decentralised energy systems

The preliminary renewable energy potential for decentralised energy systems, identified in this study, promotes rural electrification in Myanmar. The study supports the planning of decentralised renewable energy systems by identifying the village specific renewable energy potential.

As the analysis identified various renewable resource potential, there is the possibility to identify the most applicable hybrid energy mixes for each respective village. The study by Mahpatra and Dasappa (2012) identified that in terms of economic variables, decentralised energy systems are more cost effective for rural communities, as opposed to grid connection. The study further found that although renewable hybrid systems have significant start-up costs, those are more affordable in the long term than grid electrification.

The benefit of decentralised energy systems over grid connection is also identified in the study by Cherni et al. (2007), who found that although there may be variations with each village depending on various locality, socio-economic and cultural factors, it is generally accepted that decentralised energy systems are more applicable and reliable to meet the needs of isolated communities. The study further found that the incorporation of decentralised energy systems has the potential be provide energy to the grid network and provide a monetary incentive for the village to sell excess power to the centralised grid network.

As such, the results from this study and the future phases of the CORE-app have the potential to support the establishment of decentralised energy systems and provide an economic and technical case for these systems in rural contexts, as opposed to centralised grid electrification.
6.3 **Limitations and way forward**

Although every effort was made to ensure the validity of the results obtained in this study, there were inevitable limitations and assumptions which need to be addressed and detailed.

### 6.3.1 Biomass

Firstly, as each respective village crop production varies over time it is suggested that the biomass analysis undertaken in this study be carried out in the field to accurately identify the specific value for each community. It is envisioned that in the later stages of the CORE-app, there will be a possibility for local renewable energy practitioners to input village specific crop data directly into the program and instantaneously view the resulting output.

Also, the limitation of crops types included in this study was based on the amount of harvested materials per cultivated hectare. As such, the study does not consider other significant agricultural productions, which could provide vastly different conclusions regarding the feasibility and potential energy generation from biomass. Nonetheless, as the annual biomass potential was significant, and similar to values observed in literature sources, it can be theorised that the additional of other crop types would simply increase the potential and identify additional areas with biomass energy potential.

### 6.3.2 Wind

Regarding the theoretical potential wind energy, the principal limitation is the variability in wind speeds through time and space. These variations are addressed by the use of daily, monthly and annual average wind speed from varying sources. The use of datasets which utilise historic synoptic weather measurements and atmospheric re-analysis data should allow for the addressing of the seasonality issue. This coupled with the high resolution of the study areas allows for the results obtained in this study to be appropriate and valid for the method they were intended.

Nonetheless, as the wind analysis scaled wind speed data at a 50-metre height, there is the potential for significant variations with the synoptic weather measurement uses. Also, as IDW interpolation was used for the determination of wind speeds in areas with no historic measurements, it can be stated that there was a simplification used to provide wind speed values to these areas. In the future, it would be beneficial to use another interpolation method, such as Kriging or ton kriging, to address this over simplification.

Another issue in the wind analysis is the turbine assumptions and the small-scale installation limitation used in this study. Nevertheless, with the datasets used for the calculations being freely available study and the equations identified, it would be simple to recalculate the theoretical wind energy data utilising the other turbine dimensions or parameters deemed appropriate.

Furthermore, with the use of a constant air density value there is no identification of changing air density in mountainous and low-lying areas. It has also been noted that air density has a potential variation of 20-30% in high mountainous and tropical areas. As such, it may be appropriate to add a variation factor of approximately 25%, or 0.25, to future wind energy calculations.
6.3.3 Solar

For the solar analysis, it should be noted the there is potential for seasonality variations, inter-annually and intra-annually variations, as well as variations within a monthly, daily, and hourly time scale. For solar installation design and planning, these temporal variations are important but for the estimation of the solar energy capacity of Myanmar the monthly averages, coupled with the high spatial resolution the results obtained in this study are valid. Furthermore, with the varied data sources utilised and the cross validation between these sources, the results obtained in this study provide a respectable indication of the average monthly kWh/kWp solar energy potential of Myanmar.

There is also the continued possibility for further analysis and validation of the solar results obtained in this study. As there is continual cloud coverage data being updated to the MODIS archives daily, there is the potential to develop solar PV potential which has real time resource information. Although out of the current scope of this study, it would be advantageous for the development of such a tool in the future.

6.3.4 Hydropower

For the hydropower analysis, it should be noted the preliminary results mainly concern the applicability of micro hydropower installation, being 100 – 1000 kilowatt (kW), or higher. This is the result of the three cubic metres per sec (\(3 \text{ m}^3 \text{ s}^{-1}\)) criteria put in place to limit the inclusion of perennial and non-applicable river segments.

In the subsequent CORE-App development stages following this study, the hydropower analysis will have a minimum discharge requirement of 0.01 m\(^3\) s\(^{-1}\), with a maximum discharge value of 300 m\(^3\) s\(^{-1}\). The head requirement will address a minimum of 4 metres and no maximum value will be given. As a result, the study will identify suitability location and provide preliminary hydropower capacity results from the utilised dataset. The research conducted by Hoes et al. (2017) identifies the combinations between head and discharge and the ensuing presumptive hydropower potential.

Another limitation with the potential hydropower assessment was the exclusion of cells that flow into two or more neighbouring cells, where the discharge was less the minimum threshold. This produces an artefact in the resulting raster datasets suggesting an obstruction in the river that does not exist. This issue will be addressed in the follow up study, which will reduce the discharge threshold values to 0.01 m\(^3\) s\(^{-1}\), resulting in the continuation of these river segments.

In the future development stages of the CORE-App, the hydropower potential analysis will also consider the three run of river hydropower technologies identified in the future research section. This inclusion will allow the feasibility assessment to identify the technologies which are best suited to that respective river network.

6.4 Next steps of CORE-app

As this study was part of phase 1 of the CORE-app process there is a variety of future research which is currently being undertaken to both validate the results obtained in Figure 2.
Firstly, the results obtained in this study will be continually updated with the actions defined in section 6. There will also be the addition of information regarding existing decentralised hybrid energy systems provided by the Renewable Energy Association of Myanmar, to assist in the identification and validation of theoretical energy potential and observed energy potential.

Secondly, the hydropower limitations of flow and head will be reduced to ensure the inclusion of all river networks, with a subsequent expansion of hydrological factors affecting the basins within Myanmar. The expansion of runoff and drainage will be undertaken to ensure all basin that begin outside Myanmar are attributed to the hydrological conditions of their respective basins within Myanmar.

Thirdly, the potential hydropower analysis will focus on three run of river technologies, being vortex turbines, hydro kinetic and diversion channels. This will allow for a more inclusive assessment of the feasibility of each technology and the possibility for multiple hydropower installation along certain river networks.

Additionally, there were limitations placed on the location of renewable energy resources from the village. Although these distances were chosen to ensure there were no expansive distances between the resource and the village; the topography, obstructions and/or area uses were not considered. Therefore, there may be land use, topographical and/or other issues which reduce the potential energy generation from village energy profiling. These issues will be addressed in future studies to ensure resources are easily assessible and meet the applicable criteria for the development of energy installations.

Finally, as detailed in Figure 3 the CORE-app is a multi-tiered application which aims to provide not just the potential renewable energy capacity, but also build a case for the technical and economic implementation of decentralised hybrid energy systems. As such, the next stage of the application will involve the demand profiling of each village and how it will change over time.

Once this demand and potential profiling has been undertaken, there will be mini-grid simulation in which aims to provide local renewable energy practitioners with a preliminary technical and economic feasibility assessment regarding the implementation and establishment of decentralised hybrid energy systems.

The CORE-app aims to launch by the end of 2018, with additional services detailed above added periodically.
7 Conclusion

The aim of this thesis was to determine the preliminary renewable energy resource potential of all villages in Myanmar. The study further aimed to identify Myanmar’s energy potential for biomass, wind, solar and hydropower resources, with the aim to accurately provide a preliminary assessment for the purpose of identifying suitable locations for the implementation of decentralised, or off grid, energy systems, with an in-depth assessment of village potentials in the Lashio and Kayaing Provinces.

From this study, it is possible to profile the monthly resolution of wind, solar and hydropower potential throughout the entire country and all associated village locations. This study also determined the monthly potential of solar and wind resources on a 30” resolution, with the countries hydropower resources being determined on a higher (3”) spatial resolution. Biomass energy potential for the three crop types, maize, rice and sugarcane were modelled on a 30’ spatial and annual temporal resolution, with each primary residue separated.

From the results of this study, it was possible to identify the varying potential that exists both on a spatial and temporal scale. As such, when observing the village profiles there is a noticeable trend with the varying potentials between each respective renewable resource and the potential to identify an optimal mix of resources. The results of this study further support the case for localised decentralised hybrid energy systems, which are village and/or region-specific utilising the appropriate and optimal mix of renewable resources within the locality.

This high spatial and monthly temporal resolution of solar, wind and hydropower resources, and resulting village profiling allowed for the assessment of village specific optimal mixes for decentralised energy systems, meaning renewable energy practitioners are able to identify the resource potential for each village and develop an appropriate feasibility and economic case for the development of these hybrid energy systems.

Myanmar’s current focus on expanding the grid network to ensure the goal of universal electrification by 2030, might result in the continual energy inequality of rural and isolated communities. Through the establishment of renewable decentralised energy systems, to which this thesis aims to contribute, the Myanmar government has the potential to ensure the continual growth of the country in its entirety, bridge the energy gap that exists within the country, and provide electricity access, with its associated socio-economic benefits, to rural communities.
References


Doberman, T., 2016. Transforming Myanmar’s energy sector. *International Growth Centre Blog*.


ENERGY, D.W., 2016. *Global Wind Atlas*. “Global Wind Atlas 2.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU) in
partnership with the World Bank Group, utilizing data provided by Vortex, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalwindatlas.info


List of Appendices

Appendix 1: R code for village profiling output
Appendix 2: Village profiling interface
1. **Code for village profiling**

```r
# Read respective village
villages <- st_read("Location of village geopackage") %>%
  st_cast("POINT")

# get solar and wind file lists
solarfiles <- list.files("solar", full.names = TRUE)
windsfiles <- list.files("wind", full.names = TRUE)

# Village buffer
# units(dist) <- with(units::ud_units, m)
villages <- st_transform(villages, 32247)
villages <- st_buffer(villages, dist = dist)
villages <- st_transform(villages, 4326)

nvil <- NROW(villages)
days <- rep(c(31, 28, 31, 30, 31, 31, 30, 31, 30, 31, 30, 31), nvil)
days <- matrix(days, ncol = 12, byrow = TRUE)

# read area
## Areas with villages
aoi <- st_read("location.gpkg")

# sf to sp
aoi_sp <- as(aoi, "Spatial")
vil_sp <- as(villages, "Spatial")

# wind
wind <- matrix(0, nrow = NROW(villages), ncol = length(windsfiles))
for (i in 1:12) {
  raster <- raster(windsfiles[i])
  raster <- crop(raster, extent(aoi_sp), snap = "out")
  pot <- raster::extract(raster, vil_sp, fun = mean, buffer = xx)
  wind[, i] <- pot
}

# 24h production
wind <- wind * 24

# solar
solar <- matrix(0, nrow = NROW(villages), ncol = length(windsfiles))
for (i in 1:12) {
  raster <- raster(solarfiles[i])
  raster <- crop(raster, extent(aoi_sp), snap = "out")
  pot <- raster::extract(raster, vil_sp, fun = mean, buffer = xx)
  solar[i, i] <- pot
}
```

84
solar[,i] <- pot

# reorder months
# 50kW installation - the original unit is daily average kWh per kW potential.
solar <- solar*50

## water

head <- raster("headvalues.tif")
head <- crop(head, extent(aoi_sp), snap="out")
watfiles <- list.files("hydro", full.names = TRUE)

for(i in 1:12) {
  dis <- raster(watfiles[i])
  dis <- crop(dis, head, snap="out")
  dis <- resample(dis, head, "bilinear")
  if(i == 1) {
    # g*head*dis*turbine efficiency*waterused
    wat <- 9.81*head*dis*0.7*0.15 (for this study)
  } else {
    # g*head*dis*0.7efficiency*0.3used discharge
    w <- 9.81*head*dis*0.7*0.15
    wat <- addLayer(wat, w)
  }
  print(i)
}
hydro <- matrix(0,nrow = NROW(villages), ncol=length(watfiles))
for (i in 1:12) {
  pot <- raster::extract(wat[i], vil_sp, fun=min, buffer=2500)

  hydro[,i] <- pot
}
# 24h production. convert to kWh/day
hydro <- hydro*24

## If applicable transform to logarithmic scale

months <- c("JAN", "FEB", "MAR", "APR", "MAY", "JUN", "JUL", "AUG", "SEP", "OCT", "NOV", "DEC")
colnames(wind) <- paste0("wind",months)
colnames(solar) <- paste0("solar",months)
colnames(hydro) <- paste0("hydro",months)

villages <- select(villages, Vill, Vill_Pcode)
villages <- cbind(villages, wind, solar, hydro)
st_write(villages, "lashovil_v2.gpkg")
# Visualisation

Created in this process, HTML was used as it can be directly input into a webpage.

```r
months <- 1:12
plots <- list()
for(i in 1:NROW(villages)) {
  vil <- villages[i,]
  w <- grepl("wind", names(vil))
  w <- vil[,w] %>% st_set_geometry(NULL)
  wind <- data.frame(Month = months, Wind = unlist(w))
  s <- grepl("solar", names(vil))
  s <- vil[,s] %>% st_set_geometry(NULL)
  solar <- data.frame(Month = months, Solar = unlist(s))
  h <- grepl("hydro", names(vil))
  h <- vil[,h] %>% st_set_geometry(NULL)
  hydro <- data.frame(Month = months, Hydro = unlist(h))
  data <- data.frame(Month = months, Wind = unlist(w), Solar = unlist(s), Hydro = unlist(h))
  data <- melt(data, id.vars='Month')
  p <- ggplot(data) +
    geom_line(aes(x=Month, y=value, colour=variable)) +
    #geom_line(aes(x=Month, y=Solar, colour=variable)) +
    #geom_line(aes(x=Month, y=Hydro, colour=variable)) +
    theme_minimal() +
    xlab('Month') + ylab('kWh/day (Wind, Solar), MWh/p (Hydro)') + xlim(1,12) +
    scale_colour_manual(values=c("green","red","blue", "darkgreen")) +
    ggtitle(paste0("Title", vil$Vill))
  plots[[i]] <- ggplotly(p)
}

#map <- mapview(st_geometry(st_cast(aoi, "LINESTRING")), alpha = 0.95)
map  <- mapview(villages, popup=popupGraph(plots, type="html", width=500, height=500))
mapshot(map.url = paste0(getwd(), "/Title.html" ))
```
2. Interface of Village Profiling