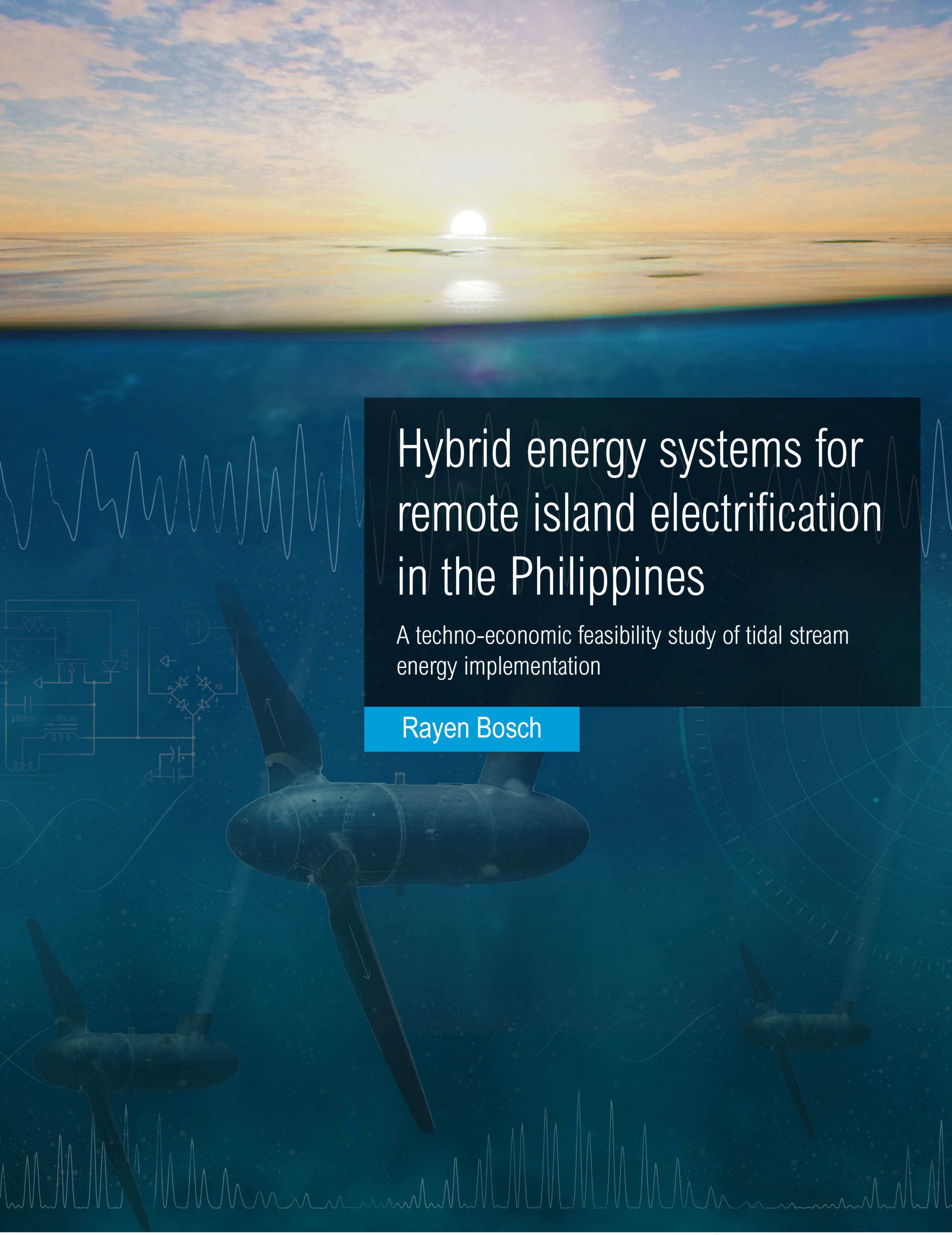

Hybrid energy systems for remote island electrification in the Philippines

A techno-economic feasibility study of tidal stream energy implementation

Rayen Bosch

TU Delft

WEnergy GLOBAL
Powering the Planet

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Abstract

Climate mitigation measures are integrated in various governmental and commercial initiatives. The sector of electrification and energy is no exception to this. For remote island communities however, the access to reliable and affordable electricity comes with additional difficulties. The effects of climate change, energy dependency and isolation are more pressing here. Island electrification therefore requires more customized or flexible solutions compared to urban environments. Using local renewable resources can significantly improve the electrification status and independence while aiding sustainability goals. The various renewable resources contain different potentials due to availability and location and any combination of multiple resources can be accompanied with uncertainty of effectiveness and complexity of integration. Seeing that island communities have direct access to ocean energy with its global potential of 16 TW, the potential for tidal energy, and in particular tidal stream energy, is assessed in combination with the more mature technology of solar PV as to reduce the reliance on conventional energy systems and investigate the possibility of fully renewable hybrid energy systems for small scale island applications.

In order to assess the technical and financial aspects of such a system, first the context of implementation needs to be clarified. Identifying the technical generation principles, resources and characteristics of each component to be integrated. To do so a framework was designed for fully renewable energy system feasibility assessment. As an assessment strategy it was decided to prioritize reliability and subsequently assess the related costs and competitiveness compared to conventional hybrid (diesel-fueled) energy systems. This was followed with a selection of performance indicators and software optimization tools to simulate the full system behavior over the desired lifetime of 20 years.

Subsequently, an expedition was held to a targeted location for the case study in this research, selected by WEnergy global Pte Ltd, to create the necessary knowledge base for future reference and investigate local tidal potential. The energy demand was quantified, and data was collected on both the local tidal energy potential and tidal system to further calculate representative tidal stream generation profiles. By using a simple tidal energy model, the representative hourly current velocity datasets could be created necessary for the simulations. An inhouse Excel based simulation model was adapted to account for tidal energy implementation, and a specialized hybrid energy system optimization software was used to validate and improve the optimization speed, accuracy and sample size. Using the available data and models the technical performance in relation to the installed generation capacity, battery storage capacity, and complementarity of resources could be analysed. The selected key performance indicators were calculated for multiple configurations and compared to a conventional hybrid energy system for its commercial feasibility. For the specific case in this study insufficient tidal energy could be generated. However similar tidal type systems were found to contain sufficient potential in combination with a suitable turbine providing up to 200 [MWh] turbine per year.

Resulting from the optimization the implementation of tidal stream energy in combination with solar PV and a battery storage system showed to be technically challenging but capable of providing in the annual island community energy need of 2.5 [GWh]. Commercially however, it remains uncompetitive even in a best-case scenario with a levelized costs of energy of 0.45 [$/kWh] compared to a cost of energy of a conventional system of 0.37 [$/kWh].

This study hopes to aid in the acceleration of sustainable electrification and climate change mitigation, the further pursuit of tidal energy implementation as a local renewable energy sources to reduce energy dependency and to provide more opportunity for improvement of socio-economic conditions in remote communities in The Philippines in line with the objectives of WEnergy Global Pte Ltd.

Acknowledgements

The completion of this thesis marks the end of an important period. My time as a student in Delft has contained many phases of both personal growth and educational achievements. After the completion of my bachelor's degree in mechanical engineering my interests in sustainability, multi-cultural environments and the global opportunities in this sector lead me to the master study of Sustainable Energy Technology. Highly motivated and with a fresh outlook I started this challenge that turned out to be one of the most fruitful experiences of my life. I would like to express my gratitude to all those who have made it the successful experience in my life.

I would firstly like to thank my parents Kanta and Boudewijn, brothers Anish and Shandil and other family members for their everlasting support, education and constant reminders to challenge myself and surpass any personal expectations. This has by far been the key to any of my achievements past and present.

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Rayen Bosch

December 2019

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Nomenclature

AC	*Alternating current*
ADCP	*Acoustic doppler current profiler*
AM	*Air mass*
ASEAN	*Association of Southeast Asian Nations*
BESS	*Battery energy storage system*
BISELCO	*Busuanga Island Electric Cooperative*
CAPEX	*Capital expenses*
DC	*Direct current*
DOA	*Days of autonomy*
DOE	*Department of energy*
ESS	*Energy storage system*
EU	*European union*
FF	*Fill factor*
FRES	*Fully renewable energy system*
GDP	*Gross domestic product*
GenSet	*Generator set*
GHG	*Greenhouse Gasses*
GIZ	*Deutsche Gesellschaft für Internationale Zusammenarbeit*
GPS	*Global positioning system*
HOMER	*Hybrid Optimization Model for Multiple Energy Resources*
HRES	*Hybrid renewable energy system*
HVDC	*High voltage direct current*
IEA	*International energy agency*
IPCC	*Intergovernmental Panel on Climate Change*
IRENA	*International renewable energy agency*
KPI	*Key performance indicator*
MOEA	*Multi-objective evolutionary algorithms*
MPPT	*Maximum power point tracker*
NREL	*National renewable energy laboratory*
OPEX	*Operational expenses*
OTEC	*Ocean thermal energy conversion*
PR	*Performance ratio*
PV	*Photovoltaic*
RE	*Renewable energy*
RES	*Renewable Energy Sources*
STC	*Standard test conditions*
TS	*Tidal stream*
USAID	*United States Agency for International Development*
WEG	*WEnergy global Pte Ltd*

1

Introduction

Island electrification comes with its inherent isolated difficulties, requiring more customized or flexible solutions compared to mainland or urban environments. The necessity of providing in energy needs by following a sustainable and renewable pathway is reflected in the effects of climate change and energy dependency that have a more direct effect on islands. The motivation and necessity for renewable island electrification in the Philippines specifically and the goal of this research will be discussed further in this chapter.

1.1 Motivation

The motivation for this study follows from the objective of "WEnergy Global Pte Ltd" (WEG) [1]: "*Powering the Planet using clean energy technologies that contributes to the fight against climate change and smart financing that gives fair and attractive returns on investments to all stakeholders involved in the process of developing power infrastructure.*" For this study the objective is to assess the commercial and technological feasibility of a fully renewable hybrid solar PV-tidal stream-battery storage energy system, for rural island application to provide reliable power supply at lower or competitive cost of energy compared to conventional diesel-powered (hybrid) systems.

One of the lower electrified yet highly populated areas in the world is that of the Asia-Pacific island archipelago including those in the Philippines, as can be seen on Figure 1.1, indicating the need for and opportunities of energy infrastructural projects in this area.

Figure 1.1 Satellite image showing electrified areas around the world [2]

Mitigating the effects of climate change is one of the fundamental reasons for pursuing renewable island electrification solutions. Changes in environmental conditions and sea level rising directly affect the economy, environment and habitability or existence of islands completely [3]. The need for transition to "greener" energy is clear. Next to this, since most current island energy systems consist of diesel fueled energy generation systems, and lack cheap alternatives, a state of quantitative and financial dependence on the supply of (non-domestic) fossil fuels was created. The often-secluded locations and limited transportation methods cause a large increase in fuel (import) price and with this also the availability and cost of energy. From similar studies it shows import rates could be as much as 200% to 300% higher than average global rates [4].

In order to effectively influence the electrification methods and status of islands multiple fields can be considered. The three main influential factors of energy transition (policy) are the environmental performance of the technologies assessed, economic efficiency of a project, and the effect on energy diversity and security [4].

Environmental performance is considered by using renewable energy sources (RES) that do not emit CO_2 or other greenhouse gasses (GHG) during operation, and hereby assist in the reduction of energy related greenhouse gas emissions into the atmosphere. GHG are the main cause of the global greenhouse effect. Some estimates show lifecycle emission to be around 10 to 20 times and 45 to 75 times lower for solar PV and wind energy respectively compared to fossil fuel-based energy generation [3].

Improvements in economic efficiency is reflected in the dependency decrease on fossil fuel-based energy generation and its supply chain following an introduction of local RES. Significant effects on the cost of energy can be made by removing this external determined cost factor. Study of a hybrid system project on a Japanese island shows possible cost reductions of 10% with the introduction of renewable energy sources [3]. In this study no comparison will be made between the pre-installment carbon footprint of different technologies. Solely an analysis will be made of technical and commercial feasibility of a fully renewable solar PV-Tidal Stream hybrid system [5].

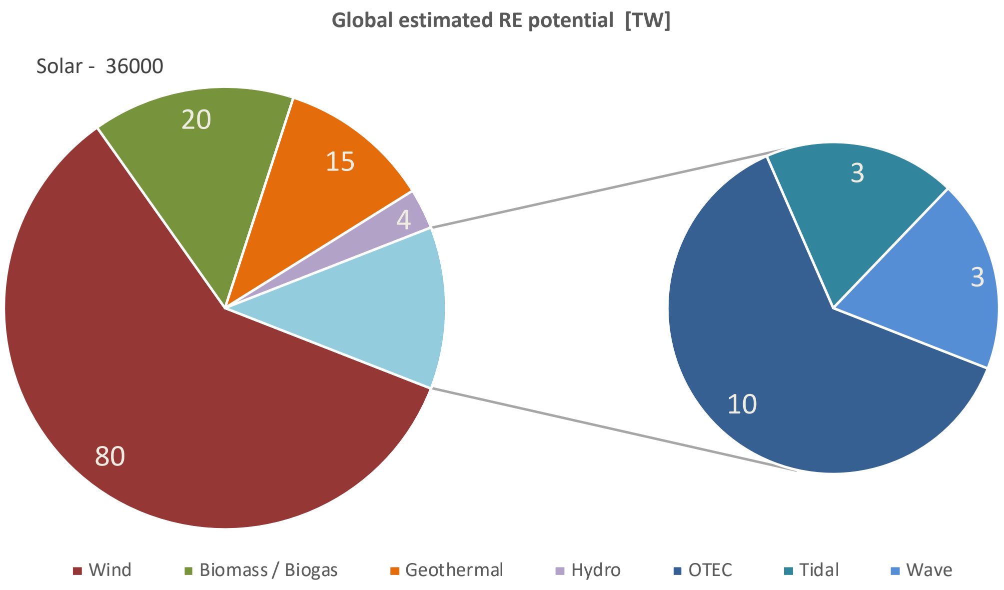


Figure 1.2 Global estimated RE potential per category, with indication of global ocean energy potential divided between OTEC, Tidal and Wave [6]

The estimated global renewable energy (RE) potential is shown on Figure 1.2 with a distinction made for Ocean energy divided in Ocean thermal energy conversion (OTEC), tidal and wave energy. Oceans contain large amounts of energy in multiple forms and significant amounts of this energy could be harvested to cover a fraction of the global energy demand (around 16 TW). Harnessing this in the island environments of the Philippines creates opportunity for market expansion into more rural areas and increase of renewable energy shares in the hybrid systems, aiding the WEG objective. Tidal stream energy is still largely in a research and development stage, yet turbines are already applied in different forms and projects. The implementation of this technology with a more mature one such as solar PV creates an interesting tradeoff between technical functionality and (commercial) efficiency. Little research has been done on the integration of tidal stream energy with solar PV for (sub-) tropical island regions in the Philippines, thus giving this study value for both WEG and the fields of system integration and rural electrification.

Using local renewable energy sources increases energy autonomy and reliability. Introducing multiple local energy source increases diversity and thereby reduces the dependency on a single form like diesel-generator sets (GenSet). Local generation of energy removes the chance of fuel shortages due to price fluctuations and supply chain problematics.

Island environments are often in possession of multiple (abundant) sources of renewable energy such as wind, solar and of course ocean energy. A characteristic of renewable sources however is their intermittency in availability or potential and the related fluctuating power output. This creates necessity for a storage solution and/or complementary generation. The security and reliability of energy supply is one of the main focus areas when designing systems with intermittent energy sources. Different approaches can be used to increase reliability such as demand side management, complementary generation, and active control of generation.

1.2 Research objective

The enveloping goal of island electrification is to increase the island's status and energy autonomy, reduce GHG emissions, and aiding the transition from the existing fossil-fueled energy infrastructure to a more (or fully) renewable solution. This feasibility study will consist of a framework for the fully renewable energy system (FRES) assessment in the Philippine island archipelago. It is thus necessary to develop an approach and performance assessment strategy for such a FRES based on the operational (boundary) conditions of the location, the technologies, the company and a number of technical and commercial parameters. The objective is to see whether tidal stream (TS) technologies can be integrated with solar photovoltaic (PV) components and a battery energy storage system (BESS) to provide a reliable and 100% renewable energy supply and if it can financially compete with a conventional solar PV-diesel hybrid system. A case study will be performed for the island of Panlaitan located within the area of the Busuanga Island Electric Cooperative (BISELCO) [7], as seen on Figure 1.3 and Figure 1.4. After an initial site assessment, it was concluded that the potential for tidal (stream) energy as an energy source needed further research here, and the location would be suitable for this study. Additionally, more general insights can then be created for WEG regarding TS technology to include in future projects.

This thesis, commissioned by WEG, crosses with previous research done by L. van Velzen [4] on the implementation of renewable ocean energy on islands. The focus here however lies not with such a general assessment of ocean energy but is aimed at researching the possibilities of specifically tidal stream energy integration for a targeted project location in the Philippine island archipelago and creating a knowledge base for possible diversification of the energy portfolio of WEG.

Figure 1.3 Philippine island archipelago, encircled the island group of Palawan [8]

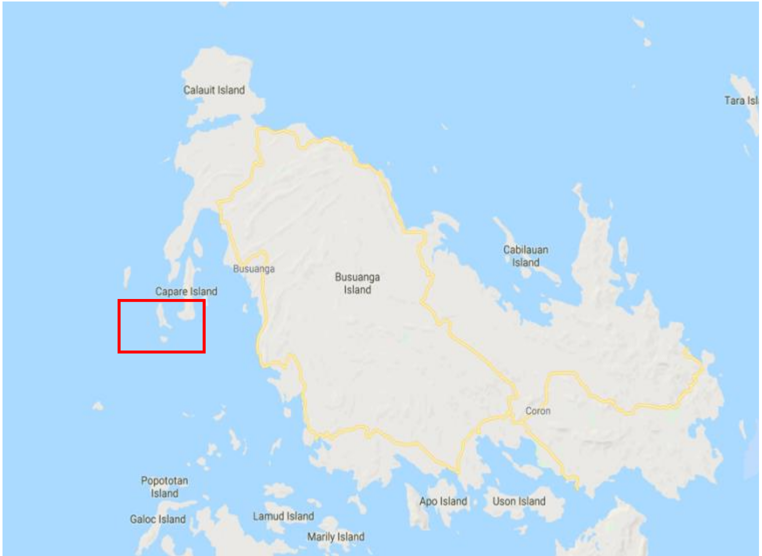


Figure 1.4 Island group of Palawan, encircled the island of Panlaitan considered in this feasibility study [8]

This study will be based largely on the research that has been done in the sector of hybrid or stand-alone energy systems. Similarities between system design using RES, differences in considerations and gaps in information can be identified. Additionally, information will be created by discussion and reflection of the performed work with colleagues and supervisors from both WEG and the Technical University of Delft (TUD). Most hybrid renewable energy systems are either complemented by diesel-powered generators or are connected to a grid to ensure reliability and few studies are found on the integration of these RES in one system for island electrification. This again emphasizes the importance of this research.

1.3 Research questions

1.3.1 Main research questions

In order to asses if it is technically and commercially feasible to combine multiple RES into an autonomous energy system, considering the locally available energy sources, scale of demand and techno-economic considerations the following main research question stands:

'What is the technical and commercial feasibility of a solar PV, Tidal stream energy and BESS fully renewable hybrid energy system for small scale island electrification in the Philippines, considering the technical implications, local (economic) environment and demand?

1.3.2 Sub questions

The following sub-questions will be addressed, formulated to assist in the development of the framework and content necessary to reach a conclusive answer to the main research question.

1. What is the necessity of fully renewable energy system (FRES) implementation, considering its advantages or barriers for Philippine island electrification?

2. What is the required methodology and approach to analyze the technical and correlated commercial aspects of such a system?

3. Which indicators and parameters best represent the technical and commercial performance of fully renewable energy systems for the application in this study and how will these be quantified to assess the performance of tidal stream energy in relation to conventional hybrid systems?

4. What is the optimal technical and commercial configuration for tidal energy integration and what are the required conditions of operation to justify a transition from a conventional to such a fully renewable system?

The first 2 sub questions are aimed at forming the theoretical approach and context. The third sub question aims at working towards a practical execution of the decided framework on a case study. The last sub question envelops the results of the feasibility study and works towards general conclusions that can be drawn from this analysis.

1.4 Structure

1.4.1 Fields of focus

Technological improvement has made the financial, institutional and social barriers of electrification more prominent, such as a mismatch between targets, policies, allocation of funds, and lack of skill [9]. The elements included in this study can be seen on Figure 1.5 containing the fields of renewable energy technologies, energy system economics and practical acquisition of data and information for the assessment of a FRES.

In multiple articles studied for this review recommendations were made for further research in the field of hybrid systems for rural applications, indicating there are still many points of improvement or unexploited fields to be looked at. A solar PV-tidal stream-BESS (PV-TS-BESS) energy system is an unusual or under-explored combination of RES, of which close to none example studies or example projects were encountered. Researching the implementation of this system for applications in the Philippines has thus added value in the fields of rural electrification and (hybrid) system integration.

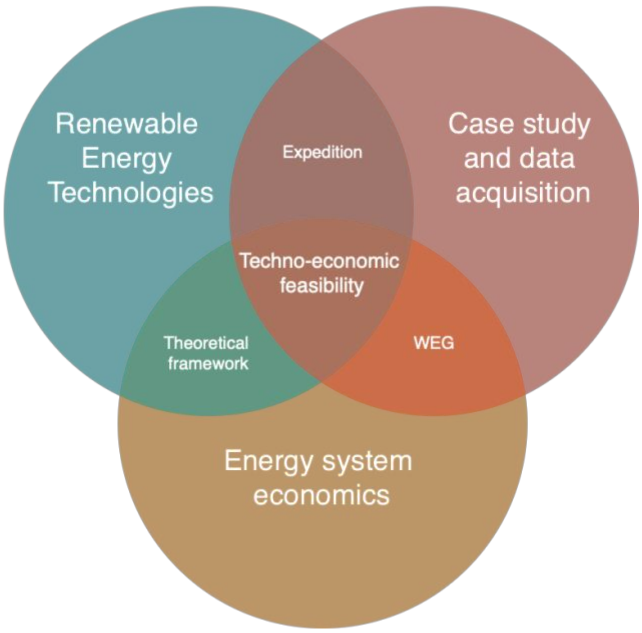


Figure 1.5 Venn diagram of correlated fields in this feasibility study

1.4.2 Report structure

Chapter 1 will describe the motivation, objectives and structure of this study. The research value, research questions and approach are described, forming the base for steps taken in the subsequent chapters. Chapter 2 covers the literature study performed for electrification barriers and advantages of islands in the Philippines, the methodology, approach and optimization choices for technical and commercial assessment and the background of the generation principles and energy sources with focus on tidal stream energy as the novel technology to be introduced. In chapter 3 the theoretical framework of tidal stream energy integration assessment and modelling will be discussed, together with the chosen key performance indicators (KPI) upon which an integrated system will be analyzed. Subsequently in chapter 4 the actual data collection and case study will be performed. An initial load profiling and climate assessment will also be made here. This in order to provide data for the technical and commercial feasibility assessment simulations of which the results will be discussed in chapter 5. An overview of the results will be discussed leading to conclusions in chapter 6 about the technical and commercial (in)feasibility of tidal stream energy implementation for both this specific project location and in general, followed by recommendations for future studies in chapter 7. This structure is reflected in Figure 1.6.

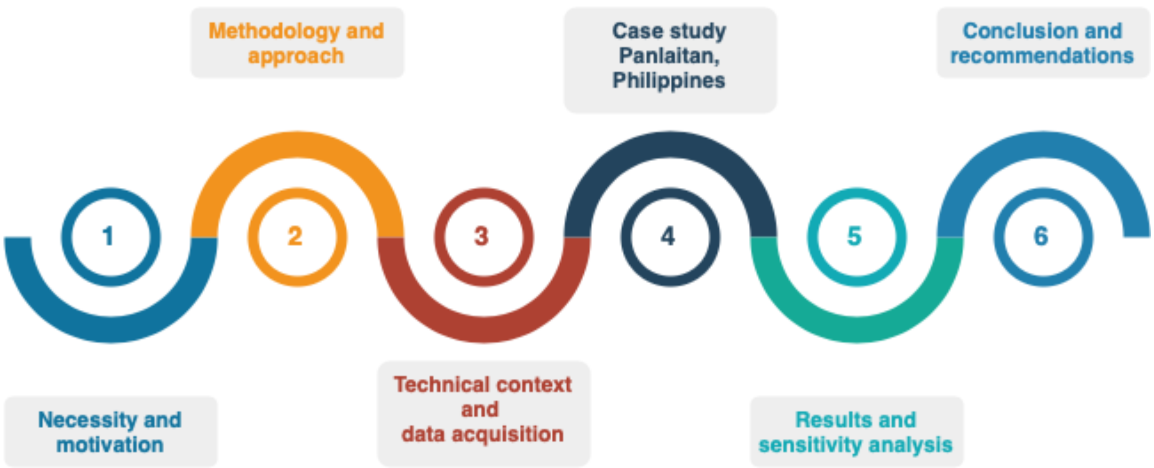


Figure 1.6 Subsequent steps taken in the feasibility research

2

Literature and context

This chapter will discuss the context and necessary background information required for the feasibility assessment and analysis of the integrated components. 2.1 forms the background of the electrification status in the Philippines and investigates the role of RES implementation with its respective barriers and advantages. A description of the possible approaches and optimization techniques is given in 2.2 followed by a thorough analysis of ocean (tidal stream) energy principles in 2.3. The hybrid energy system characteristics and the working principles and considerations related to each component are described in section 2.4.

2.1 Context of remote islands electrification

2.1.1 Electrification and transmission in the Philippines

With a population close to 105 million [10] spread out over the archipelago's 7000 islands [11], the Philippines faces challenges to provide reliable, affordable (off-)grid electrification solutions for its (remote) unconnected land areas. Recent polls show that around 20 to 25 million people have no access to electricity supplied through an electricity grid [12], and the rural areas that have access to electricity are mostly supplied by diesel-powered microgrids [7]. With an average per capita income of 100PHP (€1,80) per day and relatively high costs for fuel and its transportation it would otherwise not be affordable [13]. Reliability in terms of 24-hour uninterrupted power supply is often also not achieved with these systems, electricity is only available during certain hours of the day and black-outs occur frequently due to limited fuel supplies or system failures [12]. Additionally, supply chain barriers and environmental goals (Paris agreement) should make the continuation of diesel-powered micro-grids (or other fossil fueled systems) an unfruitful investment for the Philippine government.

The transmission system of the Philippines consists of three electricity grids, the Luzon grid, Visayas grid and the Mindanao grid, of which the Luzon grid has the largest share of generation, 72,728,369 MWh or 72,9% of total energy generation in 2018 [14]. A complete overview of the gross power generation and summarized power consumption can be found in Appendix A. Most of the generation systems are found far from the load centers making long-distance transmission lines necessary. Interconnections between the Luzon and Visayas grid by high voltage direct current (HVDC) transmission line and a submarine cable is already in place, but no connection between the Visayas and Mindanao grid has yet been made, which would unify the three principal grids and increase reliability for the main(off-grid) island(s), once connected. While the three main grids could theoretically cover all island groups, there are still many islands relying on localized power plants or power barges [15].

Power generation in the Philippines is regulated by the Energy Regulatory Commission (ERC) that issue a certificate of compliance to third party operators to ensure the Electric power Industry Reform Act (2001) standards are uphold. Power generation is not subjected to the 12% VAT, to support a lower rate for end users, however this would only have an effect on the grid connected end-users. Currently most of the electricity generation is done using conventional energy sources (fossil fuels), with some share of renewable hydro and biomass, which can be seen in Table 2.1.

Since 2002 a simultaneous phase out of oil-based gas turbines and phase-in of biomass, solar PV and wind energy has occurred. However, the relative share of renewables has actually decreased from 35.6% in 2002 to 23.4% in 2018 due to a strong increase in coal-based power generation, indicating the reliance on (foreign) fuel sources and the marginal implementation and utilization of any renewable energy potential in the Philippines. Of the 4 main renewable energy sources (solar, wind, hydro, biomass) tidal stream energy is yet unexploited source. In contrary to solar PV and wind, it has a more predictable (low) intermittent nature. Applications for remote islands would be ideal due to the available ocean area and currents increasing the possibility to implement multiple RES in a single system for reliability purposes without including conventional components. Some RES are already implemented in different projects throughout the ASEAN region (2,16% of total primary energy consumption in ASEAN) [16].

Table 2.1 Energy sources and generation percentage of Philippine embedded and on/off-grid electricity generation [14]

Source	[%] of total generation (in 2018)
Coal	52,1
Oil-based:	3,2
- Combined cycle	0,5
- Diesel	2,5
- Gas turbine	0,0
- Oil thermal	0,1
Natural gas	21,4
Renewable Energy:	23,4
- Geothermal	10,5
- Hydro	9,4
- Biomass	1,1
- Solar	1,3
- Wind	1,2

In order to meet previous objectives of 90% household electrification by 2017 and improvement of electrical services in remote island areas, the Philippine government's Department of Energy (DOE) has been cooperating with the "European union" (EU), "Deutsche Gesellschaft für Internationale Zusammenarbeit" (GIZ), "United States Agency for International Development" (USAID) and the World bank to find new solutions [7]. Possibilities for private sector participation are available, yet come with financial, technical and political challenges. Grid extension prices can vary between 6340 [$/km] in densely populated areas/countries to 19,070 [$/km] in more remote/unconnected areas. Stand-alone systems, based on RES (instead of only fossil fueled generation), can thus be a solution to grid expansion cost barriers and also form a more sustainable alternative for rural electrification [9].

2.1.2 Role and importance of renewable energy sources

The role and status of rural electrification for the pacific island region is comparable to the situation in the archipelago of the Philippines based on climate, state of electrification and energy use, as discussed in [17]. It is necessary to first build an understanding of why it is best to use RES for local energy systems and how to implement them. Since the pacific small island developing states are submissive to high costs for fuel import and climate related disasters, similar to the Philippine remote islands due to their climatological and geographical similarities, arguments to shift towards RES based energy generation can be made.

One of the biggest impacts the utilization of renewables can have is the reduction of environmental impact due to lower (or no) greenhouse gas (GHG) emissions or use of toxic (side) products (fuels). A reduction in the fossil fuel demand also influences the mining, drilling and transport activities related to the energy sector in local or foreign areas. A trend within research and development is reduction of fossil fuel reliance by increasing renewable energy shares [18]. This also creates opportunities for new companies and markets to expand their activities in the RES sector, attracting more third-party involvement and can cause a growth of economic activity and job opportunities.

There are multiple ways to simultaneously reduce environmental impact and secure energy supply, among which are reducing end-use demand for electricity, increasing efficiency of energy systems and replacement of fossil-fueled energy systems with renewable energy systems. Apart from the climatological and technical advantages there is also communal benefit by providing energy autonomy and security on local scale. Energy availability during the night can create safer living conditions and possibilities for extended education, and economic activity. The reduction of open-fire cooking facilities and diesel generator exhaust fumes also increases living conditions, health and safety. Fuel can then be used for transport and forms a lower burden on the monthly expenses of the local community. Energy security can also be achieved on national levels, by reducing the import necessity of energy resources and increasing national energy generation capacity, which can strengthen a country's political and economic position.

With hydro and geothermal power being the most used RES in the Philippines, followed by limited application of solar (mostly small household PV systems) wind or biomass in remote areas. As can be seen in Table 2.1, 73.5% of energy sources are fossil fuel based. Even though it might seem straight forward to simply use the available renewable energy source, there are institutional and financial barriers, environmental factors and skill-based problems that need to be taken into account as well. Only some areas are suitable for exploitation of renewables or ocean energy. Hydro power is a capital-intensive source, making it less useful for small island applications. Other sources must thus be utilized, like solar, wind, ocean and biomass, of which solar has one of the highest potentials due to the high year-round insolation and technological maturity. The average irradiation values are high enough to power (small) household PV systems (~100W), even on less sunny days. These small systems are mostly used for lighting, radio (telecommunication) and small household appliances or battery charging [17]. The implementation of RES, due to its variety of types and application scale, can thus provide a significant improvement from unelectrified to basic communication, lighting, and industrial appliance use, and as such introduce a remote area to the opportunities or basic welfare improvements provided by electrification.

However, time has shown that these renewable systems often do not last their expected technical lifetime due to poor maintenance or improper use. The solution to this problem is related to the local culture as much as the creation of the necessary educational and training methods. There is no one answer, due to the variety and diversity of the island communities. If a system fails, the trend is to abandon it and return to the conventional forms of energy production. This shows that in order to have system success over a longer period of time it is necessary to not only place the system but keep responsibility of maintenance and operation, as is the strategy of WEG. The solar-utility concept where ownership, maintenance and operation remain within the company or institution has shown most successful [17]. The introduction of renewables can in such a way incentivize education and expansion of expertise to further improve a developing island's capabilities to provide for and maintain its own communal energy need and activities.

2.1.3 Barriers to renewable energy implementation

A barrier Is defined by the IPCC as " *any obstacle to developing and deploying a renewable potential that can be overcome or attenuated by a policy, program or measure*" [17]. Major barriers are often not technological but institutional, social and financial.

In developing countries financial (foreign) aid programs or loans from bodies like the Asian Development Bank are often required for large infrastructure project. But the effort to have these funds allocated towards small projects is larger than the effort to direct them towards singular bigger projects. The costs for renewable energy systems are largely upfront in contrast to fossil-fuels systems. This applies to all scales which has made it more difficult to obtain financial support for lower income rural households. It is often easier for local people to pay sporadic amounts for fossil fuels than coming up with large sums of money for upfront investment. Key is thus to find a system which allows a household to pay for RE in a similar way as what small communities are used to and which they allow. Paying in small instalments at lower overall electricity costs [17].

The Philippine population has grown from approximately 81 million in 2002 to around 105 million in 2018. The GDP of the Philippines has parallelly grown from 81.36 billion to 313.59 billion [10]. Similarly, to population and GDP a correlation can be made between GDP and consumption of energy. Often higher economic activity is accompanied by higher energy consumption. The cost of and reliance on import of fossil fuels is considered a gap in energy security [19]. Even using the existing energy infrastructure can come with its problems. In order to provide this fast growth in energy demand, conventional options and expansion of the current energy system is often the first choice increasing the use of fossil fuels and thus weakening the energy security. Expanding by researching, testing and implementing the newer technologies that are related to renewable energy sources seems like a slower or more intensive process. A barrier to implement for example biomass as a RES, which would be able to use some of the existing infrastructure, is the availability of fuel and its supply chain, also the emission and pollution from burning biomass is still a factor to be considered when talking about "clean energy" [7]. However, most RES can be implemented quite fast and have more flexibility for microgrid and rural applications compared to (centralized) non-renewable sources. The increase in efficiency and maturity of technologies like wind turbines and solar PV has made them cheaper and more competitive to coal, gas or oil fueled power stations. For small scale rural electrification mostly cheap diesel-fueled generators are used.

For a prolonged lifetime, a system has to be able to withstand corrosive (humid, warm salty) air and impacts from its environment. Measures to prevent damages to key components should be in place. Since the Philippines are positioned in a tectonically active area, phenomena like volcanic eruptions and earthquakes are of effect, next to typhoons, meaning allot of stress can be put on the structural integrity of the electricity grid or remote mini grids. Weather conditions and ageing (decay) of the materials (wood and steel) used for the towers and illegal use (squatters) of the grid can cause considerable damages and inconsistencies to the transmission and hindrance to maintenance [15]. This should occur less frequently in remote areas since there are smaller communities with less irregularities or illegal electricity use. Even though the remote areas might not be connected to the mainland grids, damages to this grid slow down the possible expansion to the remote areas. This again indicates the necessity for better power resilience, reliability and autonomy.

Before installation some social barriers are usually in effect. Local landowners (villages, farmers) often need considerable persuasion to allow external parties to use their land for other purposes than their own production [20]. Additionally, in remote communities the information and skill base to install, operate and maintain RES systems is usually not available, making it almost impossible to position responsibility for servicing and maintenance operations in local communities. It is also more difficult to have someone with the right expertise, cultural background and language skills on site to do routine maintenance or report any defects. For anyone qualified, more income can be produced by using any acquired education and skillsets on the mainland or in more populated areas causing those who have been trained to leave the location they were meant to supervise. A solution might be to implement either a "grandmothering" concept where training is given to those who are rooted in the local community and are less likely to leave, or educate more people than needed so there is a surplus capacity of knowledge [17].

Another consideration to be made is the flexibility of the stand-alone system. A certain amount of redundancy or initial (over)capacity needs to be included due to the unleashed suppressed demand and yearly energy demand growth. When a community, previously connected to a limited and/or unreliable energy supply, is introduced to uninterrupted reliable clean energy it is not only the current demand that needs to be taken into account in the sizing and energy supply. An additional consideration must be made for the load which includes already existing load points and energy demand increase due to energy availability and an increase in economic activity during the first 3-5 years depending on the project. This can be estimated to be as much as 5-6% in the first 5 years leveling to around 3% annual growth in the following years [16]. This increases the necessary initial investment even further reducing the competitiveness or local support.

With electrification comes (potential for) economic growth. The current increase in energy demand in the ASEAN (association of south east Asian nations) region is around 4% due to the rapid urbanization (52,9% by 2030), the population growth (1.08% in ASEAN) and the economic growth (4,6% yearly) [16]. With this higher demand for electricity comes the increase in economic activity. Facilitating this growth by using higher shares of conventional energy options would come with drawbacks like dependence on depleting or foreign oil supplies, increasing costs for fuel and transportation, environmental damages, and investments not in line with international (climate) agreements. A way of bypassing these is to increase the amount of available RES in the energy mix. A higher share of RES has the advantage of mitigating environmental impact, reduction of subsidies for fuel and transport and (national) energy security without expensive (mainland) grid connections. Additionally, growth in installation of solar PV systems in Europa and china has led to reduction of PV module costs, which in turn reduces cost for rural application and increases implementation possibilities [17].

2.2 Methodology and framework

To analyze the feasibility of a system or technology, and to size its different components a predetermined framework or approach and a set of (decision) parameters and performance indicators is needed. There are various ways of assessing technical and financial performance and a variety of tools and software that can be used. Firstly, the outline and goal need to be clarified. Secondly the approach needs to be chosen, identifying the key parameters and indicators on which the optimization will be based. Finally, the proper tools for optimization can be selected [19].

2.2.1 Approach

A multi objective methodology is required, in order to assess both the technical and commercial feasibility of the intended system. Reliability assessment is chosen for this analysis since it represents the technical considerations and implications that might influence performance. Without the proper technology or desired component integration, a system might fail in providing the energy needed. Cost is chosen as the second base for optimization since it represents the financial aspect of designing, building, owning and operating rural electrification systems, which is key to operations within WEG. It is important to base investment decisions on indicators that represent the system's profitability and competitiveness.

A performance assessment of any kind requires a baseline to compare the performance indicators with. In this study this is a conventional solar PV-diesel hybrid energy system. The target is to reduce or replace the diesel share in the energy mix with tidal stream energy. The optimal solution also strongly depends on the type and nature of the load, which will be discussed in section 4.2, since closely matching the generation with demand has proven to lead to lower cost and higher system efficiency [18]. A minimalization of cost and increase of reliability is desired, which should result in an optimal system configuration showing its technical and commercial feasibility or conclude to a negative tidal stream implementation advice due to comparative cost or performance of conventional hybrid systems.

In order to decide on the key performance indicators (KPI) to be used, more insight into the system integration is needed for factors that can influence their performance and cost. This requires multiple approaches. Most approaches of them require an integrated model of the system components and a separate analysis of the components which will provide insight into the effectiveness of the combination or RES. Factors that can influence cost or performance (of which most are considered in this study) are listed below [5].

- Cost factors: Module cost, installation cost, maintenance and operation cost, decommissioning cost, Turbine cost, Fuel price, generator cost, carbon taxing, replacement cost
- Performance factors: Efficiency (multiple forms), Irradiation intensity, (available) land/sea area, tilt angle and orientation, Shading, Internal losses, meteorological conditions, power output, component specifications, current velocity conditions, capacity factor, maintenance cycles, Minimum and maximum operational limits, system control strategy, EES type, depth of discharge (DoD), rated capacity, gravimetric efficiency, volumetric efficiency, cycle life, operational conditions, self-consumption, installed capacity, component availability, load variation.

If cost minimization is of greater importance, such an approach would result in a clear indication of cost related performance based yet only on the factors that influence the cost. Using a reliability approach would in turn give an optimal technical outcome, indicating for example which system configuration has the lowest power losses showing performance biased configuration as optimal, but would require additional analysis of the cost related factors. It is thus of importance to prioritize the reliability of the system over the cost factors since the goal is to provide reliable electrification and indicate the financial status of such a reliable fully renewable energy system. The best result is thus achieved when both reliability and cost analysis are done at different points within the feasibility analysis. They are based on different indicators but "cross-over" influences within the complete optimization can then be identified.

Accuracy of data influences the accuracy of the KIP's. For example, a yearly average month method (stochastic method) for both weather data and load profiles require historical data which is not always available in rural sectors. An extrapolation technique would then suffice using data from neighboring areas to infer data at the targeted location. This can already be considered as an assumption influencing the accuracy of the assessment.

In general, power reliability can be defined as the capability to ensure adequate and secure supply of electrical energy to the loads. Reliability analysis is then based on sizing the components using load deficiency (probability) indicators. Some indicators that are used in similar studies are shown in

Constraining the system to configurations of which the available generated energy is equal or greater than the required load demand over a certain time period, multiple system configurations can already be excluded from the assessment. By simulating the behavior of the separate components, indicators like the loss of load risk (LOLR) can be analyzed to identify shortcomings in availability of individual components. Factors like system component availability and capacity, load characteristics and variation, system operational conditions are equally important for the complete model.

Table 2.2 Different indicator distinctions have been made each slightly different in their way of expressing performance related to power supply. In many studies found, LPSP is the most prized indicator due to its enveloping nature [21]. It includes the entire system generation and/or underproduction compared to the total load demand, as such evaluating total system performance and not only specific component performance or specific type of power loss. However, for the type of fully renewable hybrid system discussed here a Loss of Load Hours (LOLH) and Loss of Load (LOL) could provide more insight in the frequency and quantity of power shortages at each timestep compared to the overall yearly LPSP value.

Constraining the system to configurations of which the available generated energy is equal or greater than the required load demand over a certain time period, multiple system configurations can already be excluded from the assessment. By simulating the behavior of the separate components, indicators like the loss of load risk (LOLR) can be analyzed to identify shortcomings in availability of individual components. Factors like system component availability and capacity, load characteristics and variation, system operational conditions are equally important for the complete model.

Table 2.2 Reliability analysis indicators [21] [18]

Name and abbreviation	**Definition**
Loss of Power Supply Probability (LPSP)	This technique is used where probability of inadequate energy supply to load demand is considered for planning and designing of hybrid system. Loss of energy supply probability (LPSP) is the proportion of energy supply shortages with specified duration over cumulative load demand over system lifetime.
Loss of Load (LOL)	This is part of the load which is not supplied over total load time (In general one year).
Loss of Load Probability (LOLP/LLP)	It is the ratio of total power failure time over the total operational time of the system
Deficiency of Power Supply Probability (DPSP)	The probable condition of insufficient energy supply compared to the load demand. It is a criterion for evaluation and sizing of a solar PV - wind hybrid system. Mathematically represented as the ratio of deficient power supply and cumulative load demand on annual basis.
Loss of Load Hours (LOLH)	The cumulative hourly expected loss of load for one year, due to a lacking amount of installed power generation capacity at the time of interest.
System Performance Level (SPL)	A probable expectation of unsatisfied load demand (considered as System Performance Level), characterized as the number of days in which the expected load can't be fulfilled.
Loss of Load Risk (LOLR)	Probability of failure to supply daily demand of electrical energy due to insufficient generation of energy by renewable sources (even if installed capacity would be sufficient, RE has intermittent nature)
Loss of Energy Expected (LOEE)	LOEE means predicted amount of energy that won't be supplied due to insufficient installed electric generation capacity to meet the hourly load demand.
Loss of Load Expected (LLE)	The expected amount of energy which is not supplied considering that load demand is greater than generation.

Reliability indicators are usually used to evaluate the performance of a generation system against some predetermined requirements or standards. For example, certain industrial processes require more reliable power supply than residential area's due to the consequences of electrical failure, requiring a lower value of allowable load losses. Reliability analysis thus compares multiple designs and can highlight weaknesses to correct in the decision making [18].

Cost analysis can be based on using the Net Present Cost (NPC), levelized cost of electricity (LCOE), payback time or other cost indicators to decide on sizing, dispatch and optimization strategy. Since the total cost function consists of installation cost, operation and maintenance cost annually, the elements of influence on cost can be indicators (maintenance frequency, price, installation cost etc.) of cost (in)efficiency per component or system wide. Different indicators used in similar studies have been tabulated in Table 2.3

Cost restrictions are dependent on local economic environment, governmental restrictions and price competitiveness with conventional systems. Looking at the relevance of both cost and performance for this type of system feasibility analysis the most suitable indicators would be the LOL, LOLH and the LCOE, since they can consider the total system over any the desired timestep with flexibility for localized detailing. In a hybrid system this is crucial since the performance of each component can differ significantly and change independently due to operational properties.

Table 2.3 cost analysis indicators [21] [18]

Name and abbreviation	Definition
Total System Cost / Net Present Cost (NPC)	NPC gives the ratio of annual aggregate cost of the system over yearly power transfer. It includes investment, replacement and maintenance cost of the system 9complete component cost factors)
Annualized Cost (ACS)	Gives the different segments of composite cost (not necessarily annual) on annual basis such as capital cost, replacement cost and maintenance cost.
Cost of Energy (COE)	The proportional summed annualized system cost to the yearly power provided by the system. This includes every expense over the system lifetime from starting venture and capital expenses including operation and financing costs.
Life Cycle Cost (LCC)	It is the aggregate of all cost of reoccurring and one-time expenses for lifetime duration of a good
Life Cycle Unit Cost (LCUC)	It is the cost per energy unit obtained by dividing Life cycle cost with whole amount of energy produced over the system lifetime.
Levelized Cost of Energy (LCOE/LCE/LEC)	LCOE can be regarded as the minimum price at which electricity must be sold in order to break even over the lifetime of the project. Ratio of average cost over system lifetime incorporating discount rate over average production over system lifetime

2.2.2 Optimization

Optimization based on graphical construction and comparison methods, probabilistic approaches, artificial intelligence or iterative-based techniques are all with their own benefits and drawbacks depending on the kind of optimization or the available data.

The goal is to find a configuration producing an effective amount of energy with RES to satisfy load at minimal cost [5]. During optimization a large set of configurations will be tested, and most probably multiple configurations will show optimality for either cost or performance. However, to identify the most optimal configuration both objectives are considered. An increased energy output due to increased generation capacity could lower cost or increase it depending on effective consumption of this power is relatively lower. Generally, it can be assumed that under-sizing results in unreliability, over-sizing in cost and energy inefficiency [22].

Focus on optimizing one condition could exclude optimality for another. A technical optimal configuration might not fit the economic preference, creating need for a cost optimal consideration which could have suboptimal technical performance [21]. When it comes to optimization techniques to size and configure a system, they are usually classified in three groups:

- Classical/traditional optimization:
  Iterative (based on concept of energy balance and cost limitations), numerical, analytical, probabilistic, graphical construction methods
- Modern/new generation optimization:
  Generic algorithms give solutions of optimization problems based on natural advancement techniques like inheritance, mutation selection, cross over. Aimed at solving multiple problems for multiple solutions.
- Software optimization:
  Optimization software like HOMER-pro, iHOGA, HYBRID2. Not always versatile enough to include case or design specific decision parameters, but more user friendly and capable of fast (multi-objective) optimization.

A short background or description of the traditional and new-generation optimization techniques is given in Table 2.4 and Table 2.5 respectively. The software optimization tools will be discussed in the next section. New generation optimization techniques are often included in software optimization or developed by companies for inhouse use. The techniques are shortly described in terms of functionality. Traditional methods use extra processing time, meaning they can become inefficient when considering multiple parameters simultaneously for large datasets and configuration ranges. The use of multi-objective evolutionary algorithms (MOEA) [21] forms a suitable alternative. However, depending on the required detail or objectives, traditional methods could be more suitable as they provide more transparency in their process.

By stepwise adjustment of selected system variables, the effects on performance and cost can be tracked along with other effects on interconnected system parameters such as [9]:

- The effect of individual component performance on reliability
- The effect of generation timing on excess energy
- The effect of the load demand (variability) on battery performance

After optimization the process should eventually either lead to an optimal set of parameters that (for LCOE, LOL and LOLH) describing the system configuration, reliability and commercial feasibility.

Table 2.4 Traditional optimization techniques [21]

Type	Description or origin
Iterative approach	Based on a repetitive method to find a condition equal to the proposed one when the best possibilities are analysed. Relatively easy to implement and indicates faults or errors in an early stage
Probabilistic approach	Based on randomization of the variables that decide performance of a system (irradiation/currents/load). Not able to reflect the dynamic behaviour of a hybrid system but gives momentary indications.
Linear programming	A mathematical approach based on linear relationship between variables, the best method for solving complex problems by fixing one condition relative to the others and analysing the effects, however unrealistic assumptions are needed for this.
Graphical construction technique	By graphically representing the variables and results, an easier understanding of the relation between influencing factors on system cost and performance can be given. Some graphical representations however have less value, or some factors cannot be included.
Trade off method	Based on simultaneous increase and decrease of different factors around a fixed system parameter. Not commonly used for hybrid systems due to the lack of component specific adaptation criteria.

Table 2.5 New-generation optimization techniques [21]

Type	Description or origin
Particle swarm optimization (PSO)	Behaviour of fish and bird movement is the source behind this type of calculation. Uncomplicated calculation and fast speeds can be achieved, with restrictions of non-coordinate-based system problems.
Simulated annealing (SA)	Copies material annealing processes. Works on global optimization based on a technique called trajectory random investigation. Able to deal with noisy data, and to stay away from local minima.
Ant colony algorithm (ACA)	Technique on pheromone behaviour of ants in searching of shortest pathways, similarly it can optimize a problem globally and locally to reduce time and steps and backtrack to avoid unnecessary calculations.
Bacterial foraging algorithm (BFO)	Takes inspiration from aging activities from bacteria. By exponential optimization of pathways that show positive results in comparison to predetermined requirements and eliminating those that don't.
Artificial bee colony algorithm (ABC)	A proposed optimization algorithm replicating the foraging behaviour of the honeybee for decision making and analysis of options. Certain randomization involved.

2.2.3 Optimization tools

A large number of studies performed in energy system optimization use either dedicated software or self-developed tools (or models). A difference here can be found in simulation or optimization modelling. As the first is aimed at analyzing and studying the system components functionality and integration, an optimization-based model would aim to optimize a certain parameter or set of parameters. This section will give an overview of some available modelling options and describe those used for this feasibility study. An adapted overview of tools of previous studies conducted on the available software tools to model energy systems is given in Table 2.4 [4].

A division can be made between the "energy tools" based on the types of analyses that are implemented like simulation, scenario analysis, equilibrium, top-down, bottom-up, operation optimization and investment optimization [4]. An overview of the software tools most used for hybrid energy system analysis are shown in Table 2.6 . Here the software tools are classified by their functionality and inclusion of modules for tidal stream energy. Three different types of optimization are considered. The comparison-based optimization compares several predetermined scenarios, while the configuration optimization considers an extensive number of scenarios internally based on the pre-set ranges and input parameters and then provides an optimal set or scenario according to the required performance values [21]. Multi-objective optimization can be a combination of scenario and configuration, or additional optimization strategies. Indicated is also the inclusion of an ocean energy module within the software that can be used in this study for simulation and optimization of tidal stream turbine energy generation in hybrid systems, without such a module, modelling of tidal stream energy would become troublesome and could be subject to additional adaptations or assumptions for the data and calculations involved.

Table 2.6 Software optimization tool selection

Model	Simulation	Optimization	Ocean energy module	Developer	Availability
EnergyPLAN	x	comparison	Wave	Hendrik Lund, 1999	subscription
H2RES	x	-	-	Instituto Technico Lisbon, Technical university of Zagreb, 2000	Not commercially available
HOMER-pro	x	Configuration	Hydro / tidal stream	NREL, 1993 – HOMER Energy 2010	Free (pro commercial)
HYBRID2	x	Configuration	-	Uni. of Massachusetts and NREL, 1994	Free
iHOGA	x	Configuration /multi-objective	Hydro	Uni. of Zaragoza, 2013	Free (pro commercial)
RETscreen	x	Comparison	Hydro/limited ocean	Min. of Natural Resources, 1998 – OpenEI / NREL	Free (pro commercial)
TRNSYS	x	-	-	Uni. of Wisconsin and Uni. of Colorado, 1975	Commercial

Apart from these software tools there are software options like “Microsoft Excel” or “MATLAB”. In order to combine the different elements of an energy system analysis and simulate the system behavior and performance through its lifetime WEG has created its own model for (static) system simulations of conventional PV-BESS-Generator hybrid systems in “Microsoft Excel”. As this model is property of WEG and provides the necessary input and output options for a technical system analysis, it can be adapted to facilitate for tidal stream specific generation and any project specifics and can thus be used for this feasibility study. In order to provide a secondary perspective and analysis the “HOMER-pro” (Hybrid Optimization Model for Multiple Energy Resources) software was selected, which is considered the global standard for optimizing microgrid design [23].

“HOMER-pro” uses its proprietary algorithm to optimize for lowest net present cost systems for the load and location set by the user. Next to the NPC it provides a range of performance indicators such as Levelized cost of energy (LCOE), capacity shortage, own consumption (OC) and a financial and electrical analysis of the (multi-year) simulated system with options for sensitivity studies. The three main tools within this software allow for simultaneous technical and financial assessment. Th core of the software is the simulation model, which attempts to simulate viable systems for all combinations of the components considered. Allowing both timestep variations and simulation accuracy adjustment (speed vs accuracy) it gives the user room to prioritize certain aspects of the analysis.

HOMER-pro’s goal is to find the least cost combination of equipment for consistently meeting the electric load” [23]. In order to optimize for both reliability and commercial aspects the software requires information about the load profile and variability, the type of components, cost estimates for the components and any additional constraints like sizing limits. HOMER-pro then looks at all possible combinations that the user has defined. The candidate systems are presented in the results with a selected optimal configuration for each case. The user can then iterate with a more precise set of input values and further optimize the results. This freedom to include multiple scenarios and values for most parameters creates the possibility for sensitivity analyses within one simulation round. The software includes multiple packages for off-grid/grid-connected systems, and both renewable and conventional generation sources.

The simulation and optimization speed of the software, the energy source modules, sensitivity case options and combined technical and financial performance indicators that are included form an ideal tool to use for this techno-economic feasibility study of tidal stream energy implementation in FRES.

2.3 Tidal energy generation

In order to provide an assessment of tidal implementation it is necessary to understand the working principles of tidal systems, the generation principles of tidal turbines and to select (commercially) available turbines for the targeted project assessment. As mentioned, tidal turbines can provide reliable and renewable energy in remote areas. The predictable nature of tidal energy can help to compensate the intermittent nature of other RES like solar PV and reduce the insecurities around energy availability [7]. However, its energy production is dependent on multiple global and location specific factors.

2.3.1 Key terminology related to tidal power generation

Tidal stream turbines convert kinetic ocean energy into alternating current (AC). The output of the turbine depends on the water current velocity, consistency (turbulence), density and efficiency limits. From the turbine specifications like cut-in, cut-out and rated velocity a power curve can be constructed indicating the power output (W) over current velocity (m/s). The cross-sectional area, or swept area, of the blades determines the available power of the water column incident to the turbine from which energy can be converted. In general, larger diameters of blades can operate at lower velocity ranges [24].

Depending on the load and type of (hybrid) system the AC power output can be inverted to direct current (DC) power or can be transformed to be used directly for AC loads. Due to the cyclical nature of the tides and tidal currents, the power output shows a similar cyclical behavior with limited power production during points of high or low tides (slack water).

Efficiency of a tidal turbine is defined by the ratio of the power available in the water column over the actual AC power produced. This would also include any efficiencies of gearboxes and generators. The difference is also dependent on the power coefficient which is a function of the blade pitch angle and rotational speed, which is not discussed further in this report and is subject to any company design or specification. The power generation principles of tidal stream turbines will be further discussed in section 2.4.2.

2.3.2 Tidal systems and frequency

Tides are expressed in the rise and fall of sea level. These amplitude changes are caused by the gravitational forces of the moon and sun in combination with earth's rotational forces. The extend of the tidal effects is influenced by multiple factors such as the alignment of the earth moon and sun, the phase and amplitude of the tides at deep ocean or amphidromic (point of zero tidal amplitude) points and the shape and bathymetry (shape study) of the coastline ocean floor. Additionally, there are local effects of wind and atmospheric pressure and water temperature that can influence the tidal behavior [25]. Three different tide categories can be distinguished [26] as represented in Figure 2.1.

1. *Semi-diurnal*: two equally high/low tides each day.
2. *Mixed tide*: two uneven high/low tides each day.
3. *Diurnal:* one high/low tide each day.

The cyclical nature of the moon's rotation around the earth and the relative position or alignment of these celestial bodies makes it possible to fairly accurately predict the tidal cycles and the accompanying tidal currents. However, since local current, wind and geography influences are at play most harbor areas have measurement buoys in place to provide more accurate data about local tidal behavior.

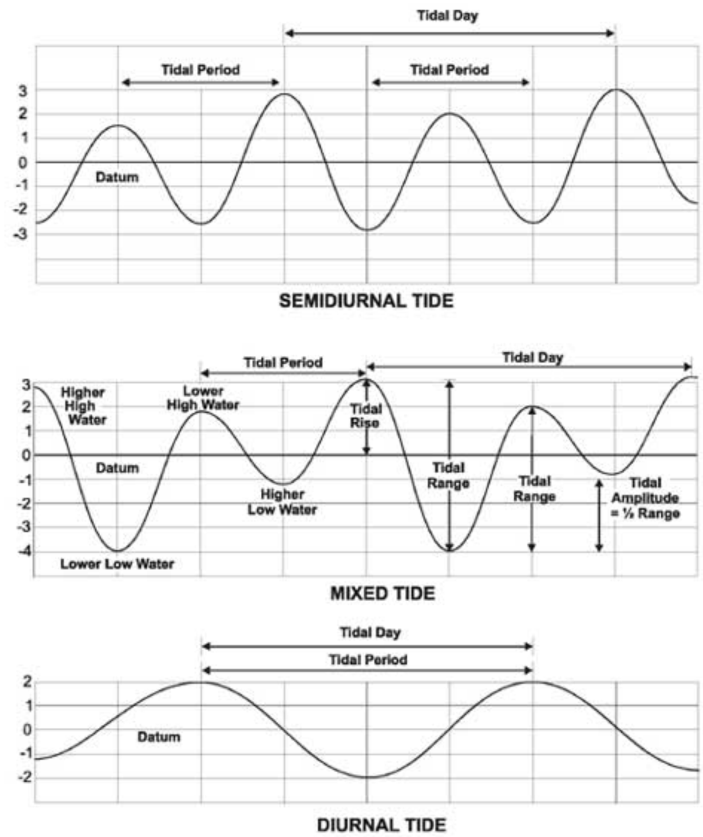


Figure 2.1 Three primal tides, y-axis: amplitude variation [m] in relation to mean sea level, x-axis: time [26].

The gravitational effects of the sun and moon create a bulge in the water mass on earth. Due to the earth's axial rotation (and inertia of the water mass) this bulge or increase in water level reaches shorelines around the world, causing temporary increasing or decreasing sea levels. As the sun also exerts a gravitational force, an alignment of the moon and sun (full moon, new moon) would create a periodical strengthening in gravitational pull and the tidal amplitude (spring tide) while the celestial position of a first and third quarter moon would have a perpendicular (weakening) effect to the sun's gravitational pull (neap tide), causing lower amplitude differences, shown in Figure 2.2.

Other effects of the constellational positions of the moon and sun like the declination (Figure 2.3) with respect to the earth's equator cause harmonic differences and location specific conditions in the tidal cycles. The location on earth directly underneath the moon is the sublunar point opposing the antipodal point. These points, together with the two corners (poles) of earth located 90 degrees from the sublunar and antipodal points lack the horizontal gravitational force component (tide producing force) exerted on the water (Figure 2.4). All other locations on earth are either submissive to a horizontal force component that pushes the water towards the sublunar point or centrifugal forces pushing the water towards the antipodal point [25]. Once every 24 hours a given point on earth will pass through the different points. This entire process is ever-going and can thus be considered an inexhaustible source of ocean kinetic energy, making tidal power the only technology drawing energy from the effects of the movements of celestial bodies [28].

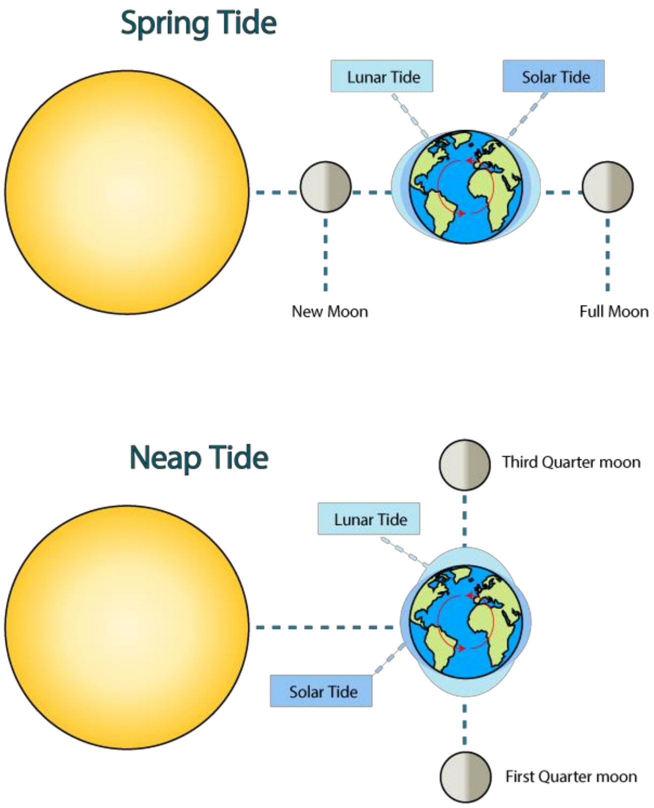


Figure 2.2 Spring and Neap tide relation to moon and sun positions [27]

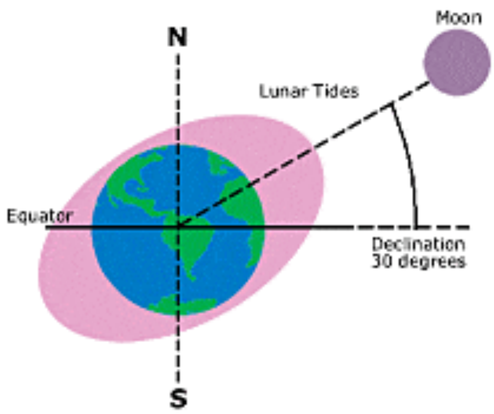


Figure 2.3 Declination effect of moon [62]

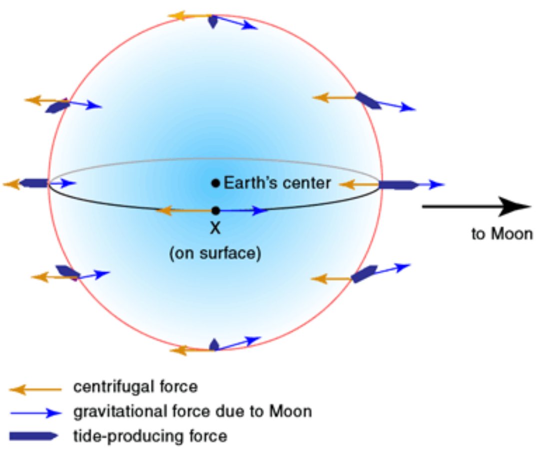


Figure 2.4 Centrifugal and (moon) gravitational forces [24]

Since tidal current speed distribution is heavily influenced by local topography it is not possible to describe in detail the exact behavior on global level. Stronger currents can be expected in channels or headlands and small changes in the surrounding areas can lead to significant lowering in observed current speeds. The gravitational effect causing the global ocean oscillational effects (tides), in combination with global topography creates areas where tidal effects are observed stronger. Tidal ranges are observed along the North-West coast of North America, Europe, Australia and New-Zealand, east coast of Africa, the Asia-pacific region, South America and numerous other localized areas [29] as can be seen on Figure 2.5 and Figure 2.6 representing the principal solar and lunar semi-diurnal constituent affected tidal areas respectively.

The effects or cycles causing the currents can be described by harmonic constituents, or harmonic elements each with their own periods and representation shown in Table 2.7. An addition of “u” in the subscript of the elements represents the accompanying current effect of the tide cycles. M_{U2} would thus represent the current amplitude corresponding to M_2.

Table 2.7 Harmonic elements of tidal systems [29]

Harmonic constituent	Period (hr)	Description
M_2 – principal lunar semi-diurnal constituent	12.42	Represents the rotational cycle of the earth with respect to the moon
S_2 – principal solar semi-diurnal constituent	12.00	Represents the rotational cycle of the earth with respect to the sun
M_4 – shallow water overtides of principal lunar constituent	6.21	Represents the change of tide wave form resulting from shallow water conditions
K_2 – lunisolar semi-diurnal constituent	11.97	Modulates the M2, S2 amplitude and frequency for the declination effects of the moon and sun respectively
K_1 – lunisolar diurnal constituent	23.93	Account for change from diurnal to semi-diurnal tides
O_1 – principal lunar diurnal constituent	25.82	Account for change from diurnal to semi-diurnal tides

Shallow water effect

Shallow water effects denoted by M_{U4} envelops the effects of wave form changes from a progressive wave in deeper water to a standing wave in shallows, bays and estuaries. This results in an asymmetric tidal current with a shorter steeper flood and drawn-out (slower) ebb [29].

Semi-annual cycle

The declination (angle) of the moon or sun with respect to the earth’s equator as can be seen in Figure 2.3, is described by the K_2 constituent or semi-annual cycle. As the earth turns around the sun the point on earth nearest to the sun will be diagonal to the equator due to the tilt angle of the earth’s vertical rotational axis. On the vernal equinox on March 21st the equator is directly under the sun (no declination). The sun then moves to the north and reaches its maximum declination on the 21st of June (summer solstice) subsequently moving south passing the equator towards the autumnal equinox on the 21st of September to reach its maximum south declination on the 21st of December. With a declination variation of 24 degrees north and south. Similarly, the moon declination varies throughout its cycle, varying between 18.5 degrees above and 28.5 degrees below the equator. This declination change takes place every 14 days but does not need to coincide with the phase changes of the moon (full, first quarter, new, third quarter). At new Moon the position is closest to the sun crossing the meridian at midday, while full moon is furthest from the sun crossing it at midnight. These cycles cause variation in spring tides throughout the year, with maxima when the sun is positioned above the equinoxes and minima at the solstices when the declination is furthest away from the equator. Extra high tides are expected at full or new moon when coinciding with a moon declination close to the equator. The K_{U2} harmonic constituent represents the difference between these mean spring and equinoctial maximum currents. This is reflected in a slowly decreasing and increasing amplitude over the year.

Diurnal inequality

The K_{U1} an O_{U1} harmonics represent the change from diurnal to semi-diurnal tides expressed in the Formzahl flow number (F_Z). This difference can be seen in Figure 2.1. The inequality or leakage of the semi-diurnal ebb current into the diurnal flood current causes a significant reduction in power output potential since it causes reduction of the tidal currents’ amplitudes. Semi-diurnal systems can generally generate more electrical power than K_{U1} an O_{U1} affected diurnal inequal systems and are thus preferred when assessing turbine deployment potential.

The locale of these tides differs around the globe. Diurnal tides mostly occur in North-west Canada, Antarctic region, South-west Australia, Gulf of Mexico, East-Java, Thailand, Sea of japan, Sea of Okhotsk and Kamchatka Basin as shown on Figure 2.5 and Figure 2.6. Mixed tides are found on the West-coast of North America, east coast of Central America, Cuba, Florida, Greece, Madagascar, The Indian Ocean coasts from Ethiopia to southern India, Indonesia, parts of West, South and North Australia, Japan and along the Sea of

Okhotsk Seen on Figure 2.7. The remaining coastlines in the world show semi-diurnal tides [30]. From this, and by using the available data from tide prediction websites [31] the type of system in the Philippines is found to be a mixed semi-diurnal tide system.

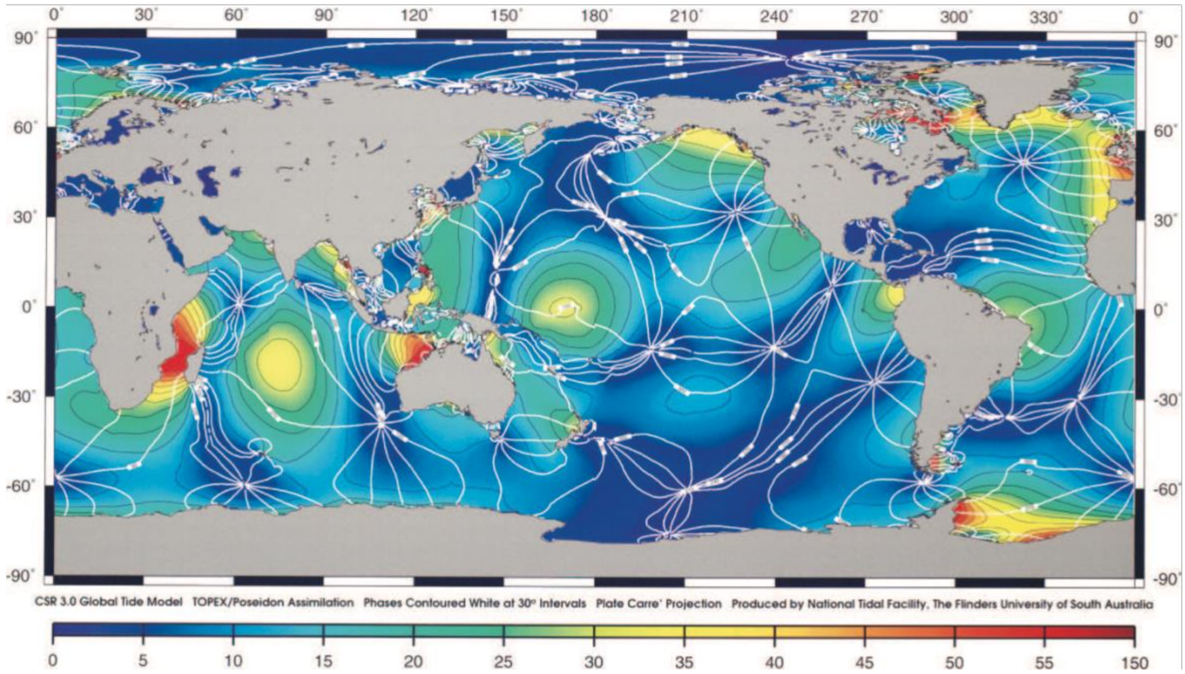


Figure 2.5 S_{U2} constituent affected areas indicating amplitude levels (cm) across the globe caused by the sun's gravitational and declination effects. Dark contour lines indicate the amplitude, the white contour lines indicate the phase (degrees) referred to Greenwich [30]

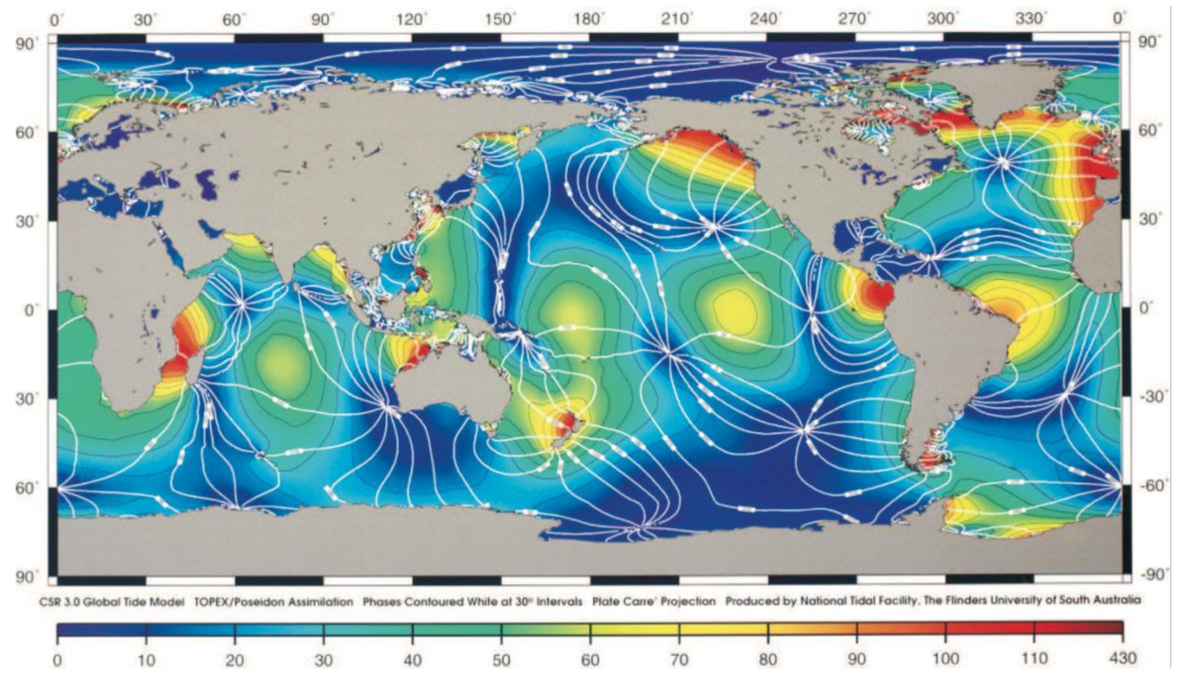


Figure 2.6 M_{U2} constituent affected areas indicating amplitude levels (cm) across the globe caused by the moon's gravitational and declination effects. Dark contour lines indicate the amplitude, the white contour lines indicate the phase (degrees) referred to Greenwich [30]

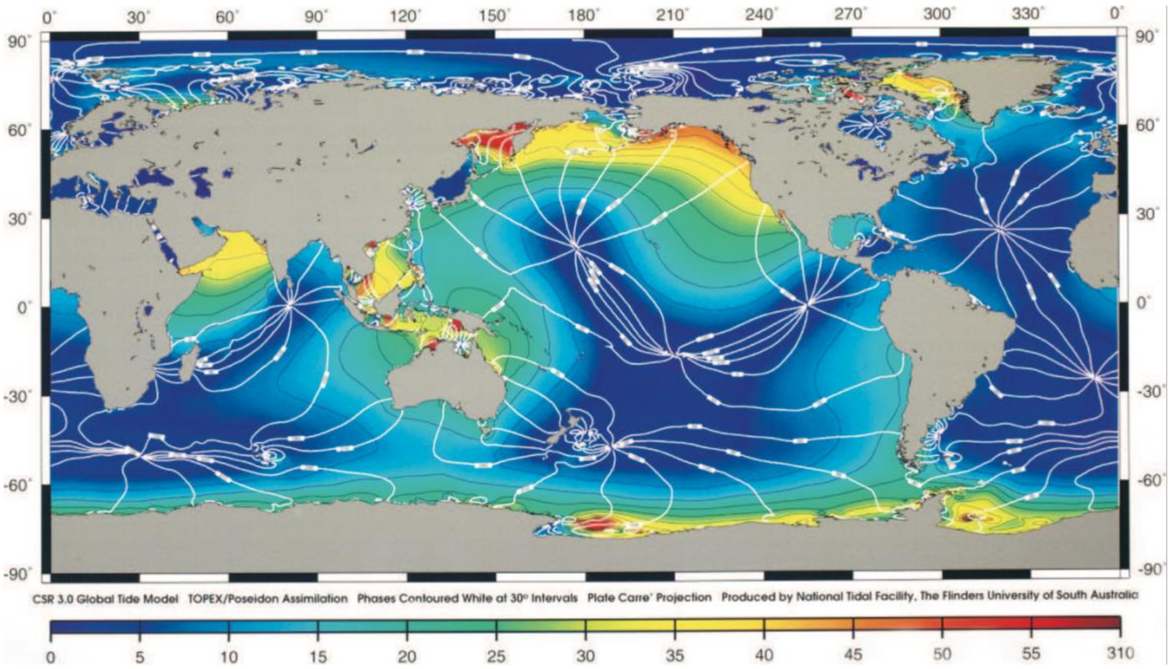


Figure 2.7 K_{U1} (O_{U1}) constituent affected areas indicating amplitude levels (cm) across the globe caused by the lunisolar gravitational and declination effects. Dark contour lines indicate the amplitude, the white contour lines indicate the phase (degrees) referred to Greenwich [30]

This ratio of diurnal and semi-diurnal inequality increases when the inequality of diurnal tides increases, with a maximum of only high water on every day. The Formzahl number thus describes this relation between diurnal and semi-diurnal constituents. The Formzahl number values and their corresponding tide types are given in Table 2.8 and is expressed with the following equation:

$$F_z = \frac{(K_1 + O_1)}{(M_2 + S_2)} \tag{2.1}$$

Table 2.8 Formzahl number and tide types [29]

Formzahl number	Tidal system type	description
Fz < 0.25	semi-diurnal	Two high and two low tide points of similar intensity
0.25 < Fz < 1.5	mixed semi-diurnal dominant	Two high and two low tide points, of inequal intensities
1.5 < Fz < 3.0	mixed diurnal dominant	Mixed between only one high tide a day, and two high tide points in the day of inequal intensity.
Fz > 3.0	diurnal type	One high tide daily, with practically no semi-diurnal influence.

The different tidal currents caused by all these effects are further defined for marker points within the cycles with flood denoting the period from low to high tide and ebb the period from high to low tide:

- Peak flood current (PFC) the fastest flood current speed due to tidal forcing.
- Mean spring peak flood (MSPF) the average spring tide peak current
- Mean neap peak flood (MNPF) the average neap tide peak flood
- Slack water current (SWC) zero current
- Mean neap peak ebb (MNPE) the average neap tide peak ebb current
- Mean spring peak ebb (MSPE) the average spring tide peak ebb current
- Peak ebb current (PEC) Fastest ebb current speed under tidal forcing

As an example of overlapping harmonic element effects on these current velocities, the MSPF of the neap-spring cycle can thus be found by addition of the M_{u2} and S_{u2} harmonic elements:

$$MSPF = M_{u2} + S_{u2} \tag{2.2}$$

Or the MNPF (M_2 and S_2 out of phase) by subtraction:

$$MSPF = M_{u2} - S_{u2} \tag{2.3}$$

As such a method for describing the cyclical effects of the tides and their related currents is given which can be used to identify the cause or timing of any intermittency in generation profiles of tidal stream turbines.

2.3.3 Ocean tidal energy generation technologies

There are different methods of converting ocean tidal kinetic energy or tidal stream energy, each with their own mechanical applications and implementation boundaries. For the scope of this research the available techniques have been narrowed down to those that can be used for ocean tidal (stream) energy conversion, excluding applications designed for rivers, hydro-dam installations, wave energy or ocean thermal energy conversion (OTEC), leaving the following applications:

- Tidal lagoons
- Tidal barrages
- Dynamic tidal power
- Tidal stream generators

Tidal lagoons are large dammed off pools of water, see Figure 2.8, that generate power by collecting water at high tide (flood generation) and emptying during low tide (ebb generation) by allowing the water to flow through turbines. It utilizes the vertical tidal range [32] and requires a construction with control to either allow water flow through the turbines or cut off the flow. This also allows the power generation to be timed according to the tidal conditions and power demand. Another method is a two-way generation where all water flows through turbines in both flood and ebb tide where the water is not held back but flows freely and constantly [33].

A tidal barrage uses a similar principle as seen on Figure 2.9, but instead of using a closed off lagoon, it uses the direct stream of tides in narrows, or the horizontal tidal stream velocity, caused by the transition between low to high or high to low tide (Figure 2.10 Tidal barrage, Oosterschelde (largest tidal barrage in the world). This type of generation is more dynamic since it is dependent on the amplitude and frequency of the tides and has limited control of water flow or storage [33]. Drawbacks of tidal lagoons or barrages, apart from their reliance on tides (like all tidal technologies), are that they require large and capital-intensive constructions which makes them less suitable for small scale applications and which can cause hinder to local marine traffic and marine life. Barrages or dams affect the sea life conditions by altering the flow of sea water which influences the water quality.

Dynamic tidal power is an unproven but promising technology based on creating tidal phase differences along a long (30-50km) man made, T-shaped dam extending from the coast perpendicularly into the sea. The dam creates tidal waves on both sides due to the phase difference, which generates a hydraulic head that can be used to power bi-directional turbines in the dam, accessible by openings in the structure. It requires less amplitude differences, making it suitable for more locations [32]. However, the investment, and construction scale limit its application, and similarly to lagoons and barrages there can be significant impact on local marine conditions.

Figure 2.8 Swansea lagoon concept drawing depicting the envisioned outlay of the lagoon [63]

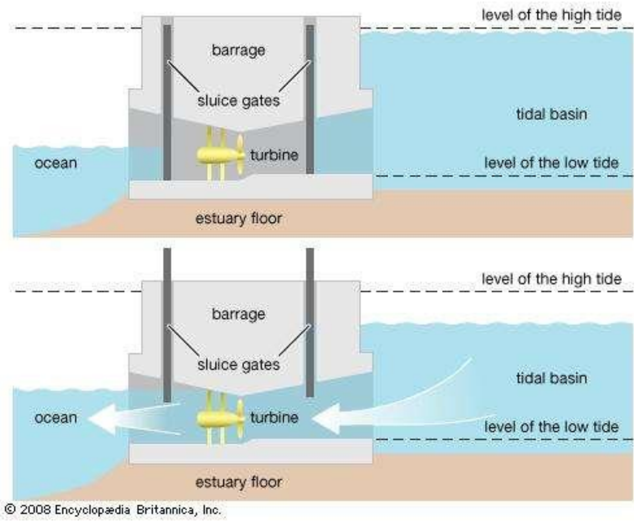


Figure 2.9 tidal lagoon/barrage generation principle of flood and ebb turbine operation [64]

Tidal turbines make use of the kinetic energy of moving water to power turbines, similarly to wind turbines that use wind as the energy carrying medium [28]. They require a constant flow of water either caused by elevation differences or tidal movement. Different sizes are available for both ocean and river applications, but generally the current velocity and its consistency is the main factor to consider. An example of a monopile tidal stream turbine is given in Figure 2.11. Its reliance on local tidal climate and the necessity for constant currents can cause limits to its applications. Since the turbines are operating in a free environment, contrary to the more protected or steady dams or barrage constructions, they are more susceptible to environmental influences like storms and waves. The tidal stream turbine is the technology that will be considered in this research, both because of the possibilities of its scale of implementation and relative simplicity of installation without cost-intensive alterations to the (marine) environment, as is the case with tidal lagoons barrages and dynamic tidal power.

Figure 2.10 Tidal barrage, Oosterschelde (largest tidal barrage in the world) [65]

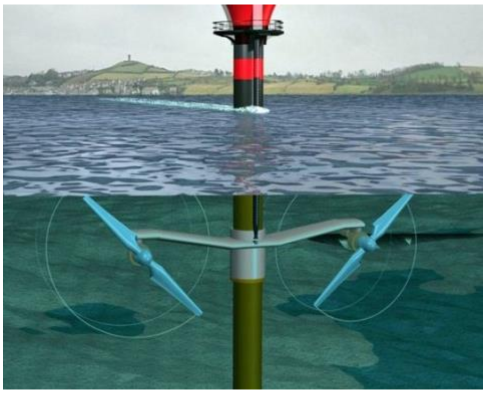


Figure 2.11 Monopile foundation type tidal stream turbine [32]

Within tidal stream turbines a distinction can be made between horizontal axis water turbines (HAWT) and vertical axis water turbines (VAWT). Both types use the kinetic energy to exert force on blades that cause a rotation. But the application possibilities can differ due to the direction of rotation and necessary (blade) area. Due to depth limitations VAWT are often used in river applications and HAWT from a certain depth in which any required clearance depth for the rotor diameter can be met.

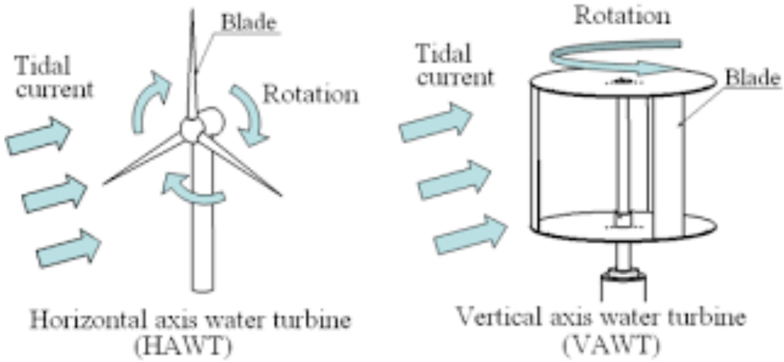


Figure 2.12 Horizontal and vertical axis turbines

2.3.4 Tidal stream turbine foundation types

Tidal turbines can be positioned in multiple ways, as seen on Figure 2.13, depending on the site of application, technical preferences, and cost considerations. The sector for offshore tidal (and wind) turbine foundations is in a state of continuous research and development, so (new) hybrid solutions can be very promising. However, the commercial availability and feasibility limits the options to those already implemented in test sites or commercial projects. Table 2.9 contains some advantages and disadvantages of each fixation type.

Table 2.9 Tidal turbine foundation overview [34]

Foundation type	Advantages	Disadvantages	Application depth [m]
Gravity based	Easy fabrication, no surface influences, more consistent flow patterns	Complex installation due to concrete volume, footprint damages and erosion	20-80
Floating	Easy to install in both shallow and deeper waters, mobile (retractable), auto arranging	Influence of surface conditions, prone to corrosion and wave loading	5-50
Semi-submersed	Modular flexibility, auto arranging,	More complex construction and installation, influence of surface conditions	5-80
Bed fixed (tripod)	No surface influences, higher power capacity (size) possible.	Complex installation due to bed fixation	20-50
Monopile	Simple design, easy fabrication, commonly used, accessible for maintenance	Possible bending and fatigue cracks in structure, seabed penetration and difficulties for installation permit due to environmental constraints.	up to 30

Based on this, and on the application considerations for rural areas, which are easy access and installation, smaller size and deployment flexibility (due to storms), a preference goes out to floating structures. Most other types require heavy barges or specialized ships (and diving teams) to construct the necessary foundation. However, depending on the bathymetry, wave conditions and installation (cost) at the target area the foundation type can be changed.

Another factor determining the application of tidal turbines is the environmental impact on marine life. Blade striking and entanglement of marine organisms forms a concern since the currents could push organisms into the operational field of the turbine. Also, the electromagnetic fields created by the generator and the acoustics created by vibrations and rotation of the blades could influence marine life, especially mammals who use echo location for navigation or foraging. Although these concerns need to be addressed, the effects of ocean tidal turbines (in low quantities) are lower than stream or river turbines, where less space is available for marine life to avoid the effects of the turbines [28]. However, more research would be needed on these effects for it to become a considerable factor in tidal turbine deployment.

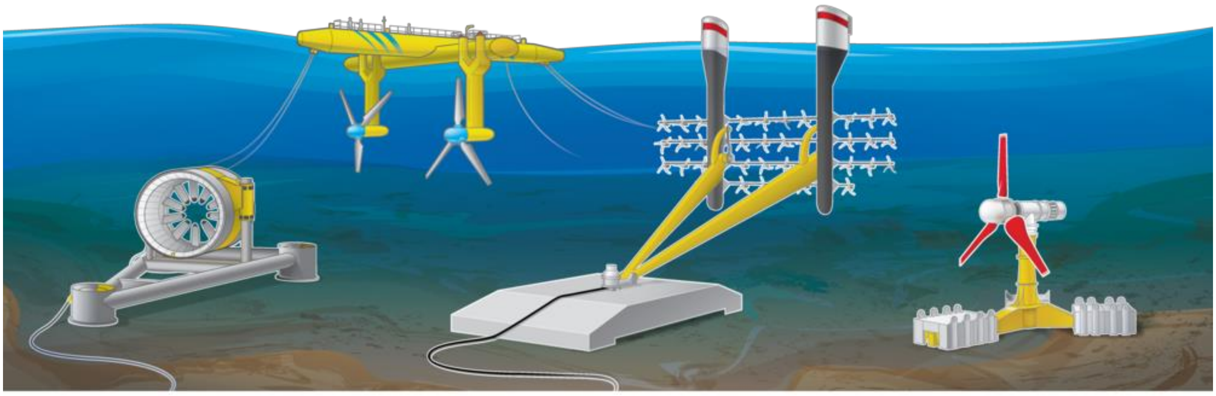


Figure 2.13 Tidal stream turbine fixation types from left to right; gravity based, floating, semi-submersed, bed-fixed indicating multiple options for tidal stream turbine deployment [27]

2.3.5 Current velocity measurements and profiling

In contrary to solar PV, temperature does not have a direct influence on the performance of tidal turbines, but influences the salinity, which together with depth of installation can have influence on the available power in a water column. Closer to the surface the current profile shows a less consistent behavior with more turbulence. From Figure 2.14 it can be seen that along the seabed the profile is disturbed by its roughness which can cause turbulence and lower flow velocities. The ideal installation depth is thus within a certain range from the surface and seabed in the section with the highest consistent current velocities. Creating an accurate profile of the local conditions leads to better decision making on turbine size and installation.

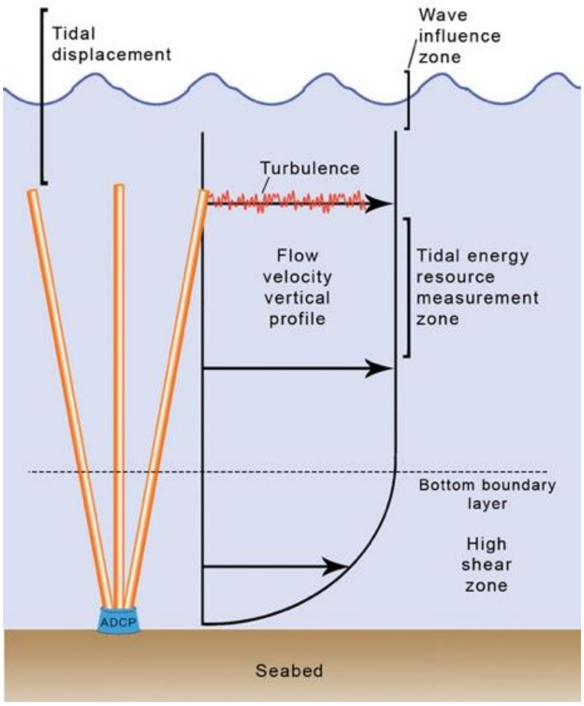


Figure 2.14 Current velocity profile sections, indicating turbulent surface section, low velocity bottom boundary and tidal energy resource zone [35]

In order to collect hourly current velocity data, the preferred method would be to perform continuous measurements at location for the duration of 1 or more lunar cycles. In general, acoustic doppler current profiler (ADCP) sensor equipment can be used either fixed to the seabed (Figure 2.14) or attached to a vessel with a Global Positioning System (GPS) and stability monitoring. Most acoustic sensors measure the current velocity (knots or m/s), direction (360 degrees), depth (meters) and water temperature (degrees Celsius) and are capable of measurement depths of 300m and continuous operation due to added battery packs. ADCP use the doppler effect by observing the change in sound pitch resulting from relative motion of the respective medium. It is an outcome of the motion of the observer (sensor) the scattered motion of signal in the medium (water) and motion of the source (sensor). An ADCP (Figure 2.15) emits and receives such acoustic signals. The emitters and receivers are placed in such an order that the sound travels in different but known direction. By measuring the shift in frequency of the soundwave between emitting and receiving the relative speed of the medium the soundwave travels through can be determined. For precision purposes it is important that the location or relative motion of the sensor to the medium is as small as possible, meaning the sensor should be placed on a fixed position or on a platform of which the relative motion can be tracked with a global positioning system (GPS) and gyroscope (for rotational movement due to waves) [36]. Current direction can be determined by using multi beam ADCP (at least 3 beam) that measure the relative velocity for specified direction (x, y, z planes) [37]. Placing the turbine in the right location determined from measurements, on the right depth and at a manageable distance from the shore is necessary to assure financial viability, ease of maintenance and increased efficiency.

Figure 2.15 Nortek Aquadopp acoustic doppler current profiler [38]

Next to the positioning of the turbine, mechanical aspects can influence its conversion efficiency. As can be seen in Figure 2.17, the pitch angle θ is dependent on the rotation of the blade along its longitudinal axis. Manufacturers determine the optimal angle and fix the blades to this angle (for most turbines) tuned for different operating conditions or blade diameters. For every turbine configuration a power curve can be created similar to the generic curves seen in Figure 2.16. The fixed pitch angle results in less dynamic control of the turbine during operation. However, since the fluctuations of water currents are not as large or frequent as fluctuations in wind currents, arguments can be made that tidal turbines require less active control to enable operation within a feasible range of velocities.

Equipment installation for actual location specific data collection is usually done after targeting possible measurement locations and collecting spot measurement for flow velocities. Spot measurements can be done using acoustic doppler current meters or mechanical current meters. By placing the instruments at different depths and making multiple measurements at each depth enough data can be collected to form approximate current profiles, which is important to locate the zone with the most consistent and powerful currents. Subsequently a full lunar cycle current velocity and direction dataset can be made by placing ADCP equipment. Together with the turbine specifications calculations on energy yield can be made. These values can then be used for further system design.

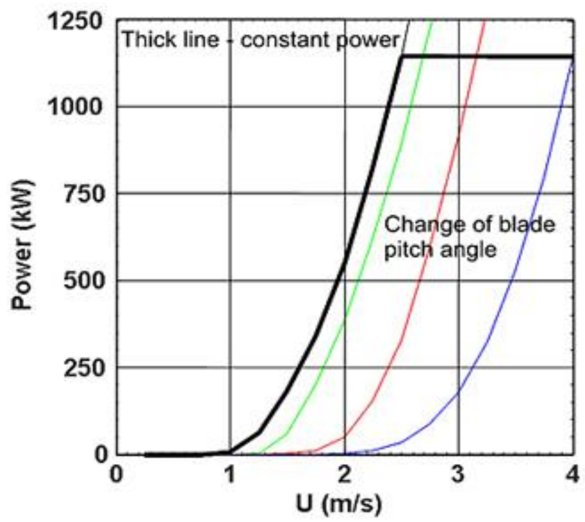


Figure 2.16 Generic Power curve of tidal turbine showing the electrical power output (kW) over the flow velocity U (m/s) for multiple pitch angles [39]

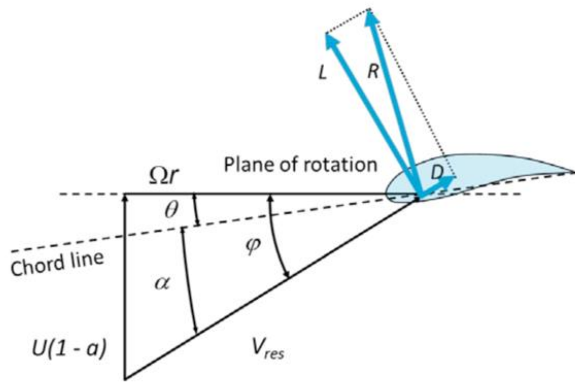


Figure 2.17 Velocity triangle on blade element, with U(1-a) the water current velocity, φ the inflow angle between the plane of rotation and the current flow, α the angle of attack, Ωr the rotational speed of the blade, V_{res} the resulting velocity of thee rotational and current velocities and pitch angle θ [66]

2.4 Fully renewable energy system characteristics

A hybrid renewable energy system can be defined as: "*An arrangement of renewable power generation components with appropriate storage, and a feasible amalgamation with conventional generation components, considered as a hybrid energy system, or micro-grid*" [21]. A distinction can be made between grid connected renewable energy systems and stand-alone (autonomous) systems. In this study the fully renewable hybrid energy system is considered. Most applications for rural areas will fall in the category of stand-alone systems since connection with a mainland grid is not possible. Generally, a system with only one renewable energy source would not provide similar reliability or energy output as a conventional system. However, a combination of multiple RES integrated into a single system, could provide reliable, affordable and clean energy. Using a hybrid system can also have prolonging effects on BESS lifetime compared to single RES systems, since the (dis)charge frequency and or depth can be better managed in accordance with the subsequent or complementary power production (e.g. solar PV during day, wind during night). Often diesel generators are still included in micro-grid design to support reliability by providing a base load and peak load coverage.

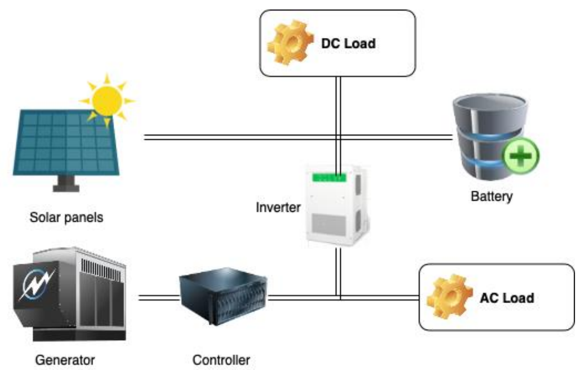


Figure 2.18 Solar PV - Diesel - BESS conventional hybrid system topology (simplified)

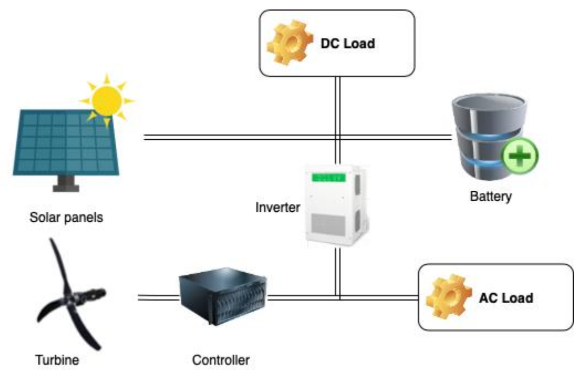


Figure 2.19 PV-TS-BESS fully renewable hybrid system topology (simplified)

A simplified topology of a conventional hybrid system (Figure 2.18) and with an optional diesel generation component (Figure 2.19) are given. RES in general are characterized by their variable and intermittent nature that can lead to uncertain power availability. Because of this it is necessary to combine multiple sources to increase overall reliability, efficiency and reduce operational cost [18]. Finding methods to integrate the individual RES considering their constraints is thus crucial.

Although the benefits of FRES can be great, there are some possible drawbacks that need to be taken into consideration, like:

- Dependency on geographical location (marine environment, land profile)
- Dependency on environmental conditions (climate, insolation, wind/water velocity)
- Intermittent nature of generation and its effect on the complementary performance.
- Higher initial investment costs and required expertise.

By adding a storage component (excess) energy can be stored during overproduction which can be used during moments of intermittence or to satisfy load demand during underproduction. By having multiple energy sources that work in complementary or sequential manner the size of the storage component could be reduced due to the generation overlap, in contrary to single renewable energy source systems [18]. The underlying concept is to provide the same base load energy as conventional systems by matching the generation profiles of the RES and using BESS to bridge the generation-demand mismatch, instead of providing energy with continuous (scalable) on-demand diesel generators. RES also have an effect on system cost (reduction) due to the overall lower operational expenses (no fuel cost). In order to size the components different approaches or criteria can be used as seen in section 2.2. The methodology and approaches used will be discussed in chapter 3.

Numerous combinations of RES can be made, of which solar PV and wind energy are currently in high demand due to their complimentary nature and technological maturity [21]. There is no additional cost related to their accessibility, in contrast to biomass or hydrogen (fuel sourcing). However, the non-uniformity in generation components requires a more in-depth matching process and complex control system, adding upfront capital costs [19]. Another factor to include in the design process is that renewable energy systems do not produce on-demand energy, as is the case when switching on or off (conventional) generation units. This results in different energy production (profiles) of the different components, and a mismatch between the generation and demand profiles. When aiming to provide 24/7 uninterrupted power supply, these energy needs to be managed with ESS components. Another way is to use a RES that has a less intermittent and more predictable nature, like tidal energy.

The Flexibility of FRES systems together with the ability to use local resources in different locations has its advantages for rural electrification over conventional energy generation facilities (more centralized, fuel infrastructure). After initial capital expenditures (CAPEX) there are lower operational expenditures (OPEX), lower environmental impacts and more energy autonomy for local communities, without the need for expensive electricity grid connections or infrastructures between islands.

2.4.1 Types of fully renewable energy systems

Since each RES has its own typical generation profile, implementation boundaries and requirements, the combination of multiple sources can be complex. Different RES can be combined in different configurations with each other. There is a distinction that can be made between higher intermittent sources (solar, wind) and more predictable or steady sources (hydro, biomass, geothermal), the latter having higher restrictions for application due to necessity for complementary structures. Finding the suitable configuration of FRES is thus related to the topography, accessibility, the potential of available energy resources and the types of required energy (heat or electricity). In order to provide higher reliability of supply and reduce the size and related cost of generation components, it is advisable to combine an intermittent source with a more predictable or steady source. Some (common) configurations are shown in Table 2.10, a plus indicating combinations that have been seen in similar studies and that are combined considering their complementary nature, and a minus indicates combinations that are less likely to be combined. The typical generation profiles of wind turbines, solar PV and tidal turbines are shown in figure Figure 2.20. Generators running on biomass, hydro installations and geothermal installations have a fairly steady generation profile similar to diesel generators.

Table 2.10 Possible RES combinations in FRES systems depending on intermittency of generation

	Solar PV	Wind	Hydro	Ocean	Biomass	Geothermal
Solar PV	x	+	+	+	+	+
Wind	+	x	+	+	+	+
Hydro	+	+	x	-	-	-
Ocean	+	+	-	x	+	-
Biomass	+	+	-	+	x	-
Geo-thermal	+	+	-	-	-	x

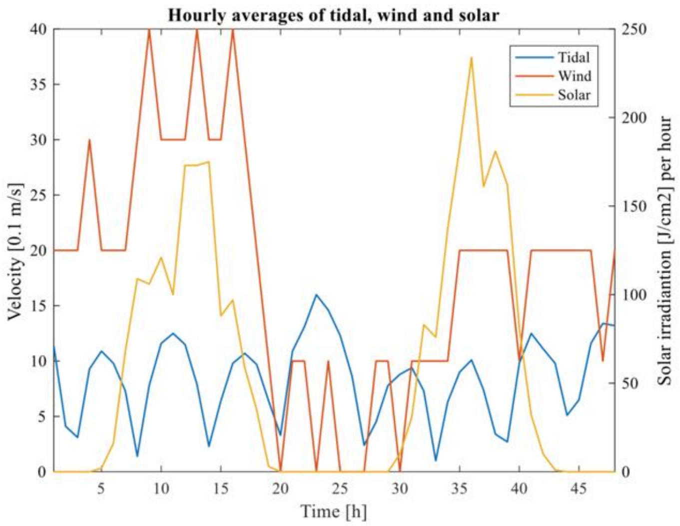


Figure 2.20 Typical generation curves for solar PV, wind turbines and tidal turbines indicating the possible complementary power or mismatches during operation [16].

2.4.2 Tidal stream turbine generation principles

As described in section 2.3.3 there are multiple ways of converting ocean kinetic energy. Tidal stream energy conversion is comparable to wind turbine energy conversion. The principles of generation are similar yet use a different medium and operational range.

Ocean currents move slower than wind currents, but due to the higher density of water (1020-1030 kg/m3) lower velocities are needed to generate the same amount of power as for wind turbines. A current moving at 12 knots (6.17 m/s) could generate as much energy as wind moving at 110 knots (56.59 m/s) To model a tidal stream energy system, different elements need to be included such as the tidal current speed profile and the turbine itself. A more in-depth representation also includes the turbine systems like the drive train and generator. Mechanical analysis however is not within the scope of this study and the turbine performance will be modelled according to the specifications provided with selected turbines.

As can be seen in Figure 2.21 a turbine converts kinetic energy of water into mechanical rotational energy (T_m), which is converted to an electrical torque that drives the generator (T_e) and is finally converted into electrical energy by the generator. The tip speed ratio of the turbine can be controlled by the generator angular speeds (w_g) affecting the drive train and in turn influencing the rotor angular speed (w_r) [40].

The power production from a turbine depends on the available (hydraulic) power available in the current which can be calculated with:

$$P_{current} = 0.5\rho AV^3 \quad (2.4)$$

With ρ the seawater density, A the rotor area or swept area of the water column and the current velocity V. The actual AC electrical power that could be produced is submissive to a power coefficient (C_p) which is a product of the tip speed ratio and the turbine blade pitch angle [29]:

$$P_{turbine} = 0.5\, \rho\, C_p\, A\, V^3 \tag{2.5}$$

The power coefficient is limited to 0.593 (Betz limit). This is the theoretical extraction limit of 59.3% dependent on aerodynamic losses and the number, shape, weight and stiffness of the blades among others. A passive control is used in order to operate the turbine at its rated speed, controlling the blade rotational speed (if possible) and pitch angle to maintain rated power point operation. No blade pitch control results in limited turbine control. Since the actual turbine design will be done by a third party, no in-depth analysis or turbine design process is discussed here. Smaller sized tidal stream turbines often do not have active pitch control and rely on material properties to influence the operational range of the blades at certain limit current velocities. No active influence of the turbine in the rated velocity range is possible and it is thus necessary to either remove or deactivate the turbine above any limit conditions. A way of expressing the effectiveness of energy conversion by a tidal stream turbine (or any generation component) is the capacity factor (Cf) given by:

$$Cf = \frac{Annual\ energy\ production}{Rated\ capacity\ \cdot\ 8760} \tag{2.6}$$

With the rated power capacity in [kW] as given in the specifications, annual energy production in [kWh] as calculated for a certain location and the number of hours in a year (8760).

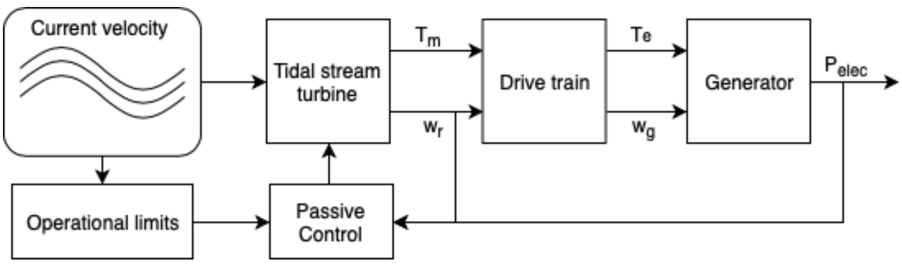


Figure 2.21 Tidal current energy system block representation [40]

2.4.2.1 Turbine selection and cost considerations

A technical feasibility study requires narrowing the scope from conceptual turbine designs or research phase technology, to commercially available or test phase technologies. A thorough analysis was made of 20 companies involved in tidal energy or tidal turbines manufacturing, selecting the turbines or tidal technology based on the following criteria, partially determined by specification sheet analysis and discussion with WEG staff [5]:

- Country in which the company has facilities: Since transport and construction considerations can be of effect, some regions or countries are less suitable. Most companies have multiple facilities around the world or have local (ASEAN) representatives, which would positively influence their application possibilities in the Philippines
- Turbine type: Due to application possibilities, and proof of concept, some technologies are less suitable for ocean application. Distinctions can be made between vertical axis, horizontal axis,

spiral axis or open/ducted turbines. It is always necessary to tune the technology choice to the application.
- Orientation type: An auto-arranging (floating) tidal turbine requires a large footprint area in which no other marine activities can take place, this can be a limitation when operating in areas with limited available space. Bidirectional turbines do not require the same area yet have the disadvantage that the operational directions need to be determined beforehand which requires accurate data collection of the specific location.
- Foundation types: As mentioned in section 2.3.4 different foundation types are possible, yet not every combination of turbines and foundation is suitable for certain locations or even commercially available.
- Power rating: Depending on the application and target area the size of the turbine is important for modularity of the total energy system or over/under generation considerations.
- Dimensions of the turbine (blade diameter/ swept area /fixation structure): A larger turbine requires a larger operational area, which is not always available or safe in relation to the marine environment, or island economic activities like fishing.
- Operational velocity range: The rated speed, cut-in/ cut-out current velocity of the turbine should match the available current velocities at the site, for maximized efficiency.
- Required clearance depth: A certain water depth is required to position the turbine in the most effective operational depth and to prevent interference with the surface, the seabed, or marine traffic during tide changes.

After initial assessment of the factors above, a selection of turbines was made that could operate under the estimated Philippine conditions. Price indications would also be taken into consideration however, these were often not given in pre-feasibility stages. With current velocity data, power yield calculations can indicate the most suitable option. A summarized technical overview of the selected turbines is given in Table 2.11. For this selection a range of turbine power ratings (20-125 kW) was kept ensuring options for different scales of applications, depending on the exact data of the location. However, the performance of the SIT-250 showed most promising.

Table 2.11 Overview of selected tidal turbines and initial selection criteria

Company / Turbine type	**Tocardo T1**	**Guinard P-154**	**Schottel Tidalstream SIT-250**
Manufacturer location	Netherlands	France	United Kingdom / Germany
Fixation types	- retrofit array - floating - gravity/bed based	- floating - gravity/bed based	- floating - gravity/bed based
Power rating (kW)	125	20	70
blade diameter (m)	3.1 or 6.3	1.54	4.0 or 6.3
cut-in (m/s)	0.4-0.9	1	0.5
cut-out (m/s)	2.6-6.8	3.5	4
survival water speed (m/s)	4-9	-	-
swept area (m2)	7.54 / 31.17	1.86	12.56 / 31.17
axis orientation	horizontal	horizontal	horizontal

To quantify the cost aspects related to tidal stream turbine technology implementation, A price quantitative ($/kW) indication is deducted from initial price indications in the emerging tidal stream energy market and cost trends in the hydro and offshore wind sectors. However multiple reports of the National Renewable Energy Laboratory (NREL), International Renewable Energy Agency (IRENA), and International Energy agency (IEA) have included hydro technologies in their statistical reports, no distinction is made for ocean kinetic energy. Cost estimations and statistics of tidal stream turbine technology begin to appear in reports from 2017 with exception to some specific studies into the ocean energy potential of the marine energy council [41] (2015) and the World energy council [42] (2016). Unclear is if these values are turnkey cost or less enveloping values. The assumption here is made that these costs represents the entire deployment process.

Most cost assessments found in these reports are based on projected costs, and not experience data. The influence of assumptions in cost predictions has a significant influence on the cost assessment of projects, which can differ substantially depending on the size and location of the project, the stage of the technology development and the level of detail in the assessment. From a report of Ocean Energy Systems, it follows that a preliminary cost assessment of a technology in pre-commercial phase can have a sensitivity range of +/-15%, thus also applicable to any cost assessments made for tidal stream energy [41].

When looking at the trend of LCOE reduction over cumulative installed capacity as in Figure 2.22 with a cumulative installed capacity of tidal stream turbines of around 27.5 [MW] in 2018 with an estimated cumulative capacity of around 40 []MW for 2019 a cost reduction trend of 10% can be deducted (from 420 to 380 $/MWh) [43]. Looking at the cost breakdown of tidal stream turbine technology in Figure 2.23 the majority of the cost can be found in the capital expenses (CAPEX), meaning a cost reduction will for the most part be due to a reduction of CAPEX and thus be largely reflected in the cost per kW installed before operation. Applying this 10% reduction to the estimated price per kW of 2500 [$/kW] (assumed upper boundary) from IRENA, leads to a value of 2250 USD/kWh in 2019 for tidal stream turbines. The price uncertainty described for a pre-commercial phase preliminary cost estimation can be used ranging it between 1912 and 2587 [$/kW].

Comparable industries have shown learning rates between 10-30%. The offshore wind industry, closely comparable to the offshore tidal turbine industry has shown learning rates of around 15% [41] or as high as 20% between 2010 (0.159 $/kWh) and 2018 (0.127 $/kWh) according to NREL. These costs however are influenced by a large range of factors like economies of scale, (project) efficiencies, improved reliability in both operation and reduction in maintenance and overall design improvements

In the closely related hydro sector prices have fluctuated between 1171 [$/kW] installed in 2010 ending at 1492 [$/kW] installed in 2018. This fluctuation can be related to the cost of civil constructions. Since tidal stream turbines, as considered for this project, do not require large scale civil engineering elements, a lower boundary cost assumption of 1492 USD/kW can be followed. Preliminary price indications for tidal stream turbine project specifically vary significantly with changing implementation scale and location. According to [41] cost values of small-scale projects (lower than 500 kW) can vary between 3000 and 5000 USD/kW (2018). World Energy Council reported estimates of prices are in range of 3300 USD/kW in (2016) depending on installed capacity or project size [42]. Overall learning rates are predicted by [41] and between 10-30% for CAPEX expenses (in line with offshore wind). However, from these estimate no definitive costs can be deducted since these values are based on different testing/development phase project assessments.

For adaptation of the price sensitivity for this assessment a cost of 1750 $/kW is used placing above the cost of solar PV, with a sensitivity range (1500 – 2500). The purpose of this is to simulate the (hypothetical) effect of introducing a second components in the hybrid system with a higher price value as that of PV, since a lower price would be unrealistic considering the trends discussed. Optimality can be found for a technology's installed capacity and accompanying cost related to its effective energy yield. Due to this a variety of configurations with preference for cheaper or more expensive components can be found.

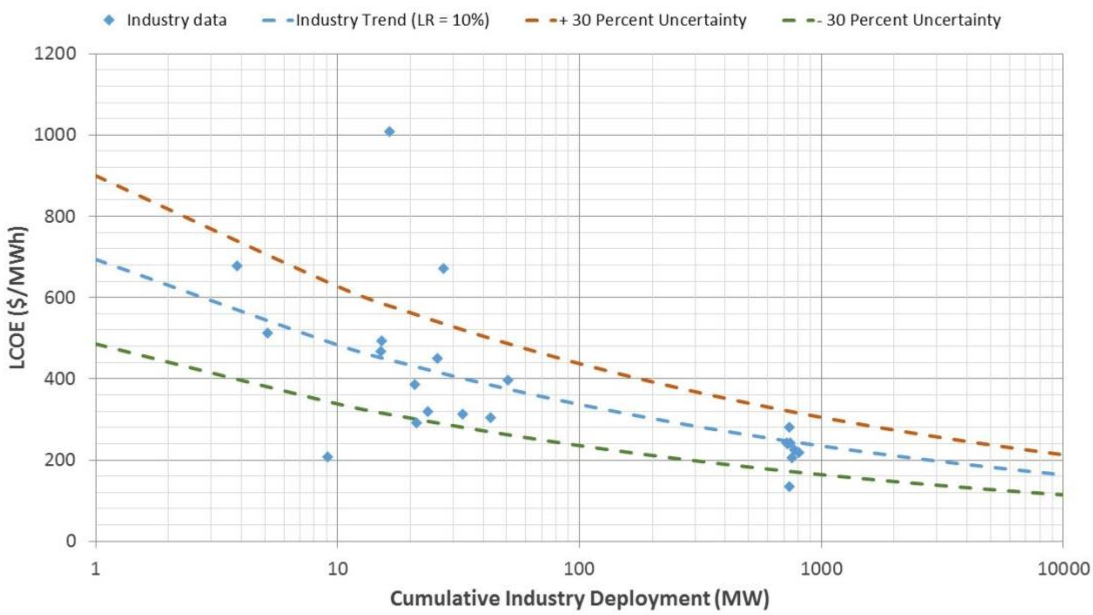


Figure 2.22 LCOE over cumulative industry deployment of tidal stream turbines indicating reducing trend in LCOE with uncertainty indication [41]

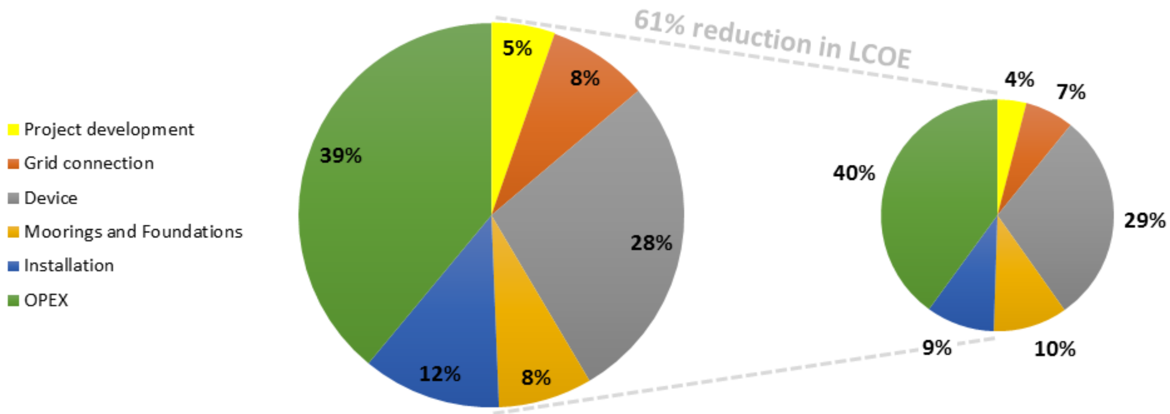


Figure 2.23 Tidal stream project cost breakdown and projected breakdown for reduced LCOE scenario in case of higher installed cumulative capacities and maturity of technology [41]

2.4.3 Photovoltaic energy generation

2.4.3.1 Photovoltaic generation principles

The light emitted by the sun contains a spectrum of energy levels. This energy is denoted as irradiation [W/m^2]. The sun's relative position can influence the radiation levels and thus directly the amount of energy that can be converted in PV cells. The relative sun position is dependent on the rotation of the earth around it, and thus on the time of the day, month, year and the location on earth from which it is determined. It is crucial to determine the correct irradiation values and parameters with which the power yield can be calculated. This is often done with weather station data and software, like "PV Sol", designed to calculate irradiance values and power yields for PV systems at any given location on earth.

The photovoltaic effect converts the energy from solar irradiation into electrical energy or direct current (DC). The power output of a PV module is dependent on the location on earth, local meteorological conditions and input energy provided by the sun. Since this can vary significantly the standard test conditions (STC) are used to express the PV module performance specifications and the output power. STC conditions are set at an irradiance of 1000 [W/m2], a module temperature of 25[°C] and a spectrum of a latitude of 35 degrees north (AM1.5) [44]. The output power unit is determined as watt peak (W_p) under STC. Temperature increase and other effects like soiling and module degradation over time have a negative effect on the power output. During actual operation the module temperature can be higher than STC conditions and other loss mechanisms might be of effect which causes the actual power output (W) to be lower than the nominal peak value [45].

Parameters used to characterize the solar cell performance are the peak power output P_{max} [W], the short circuit current density J_{sc} [A], the open circuit voltage V_{oc} [V],and with these the fill factor (FF). When a solar cell is illuminated (STC) a J-V (or power) curve can be made from which these parameters can be determined [45]. The short circuit current is the current that flows through the external circuit of the solar cell when the electrodes are connected to each other (no load). The short circuit current density J_{sc} $[A/m^2]$ is the short circuit current (I_{sc}) expressed without the solar cell area dependence. The open circuit voltage is the voltage at which no current flows (no connection) and is equal to the maximum voltage a solar cell can produce when illuminated. To maximize power output, it is preferred to operate at the maximum power point (MP) of the power curve, which requires a maximum power point tracker.

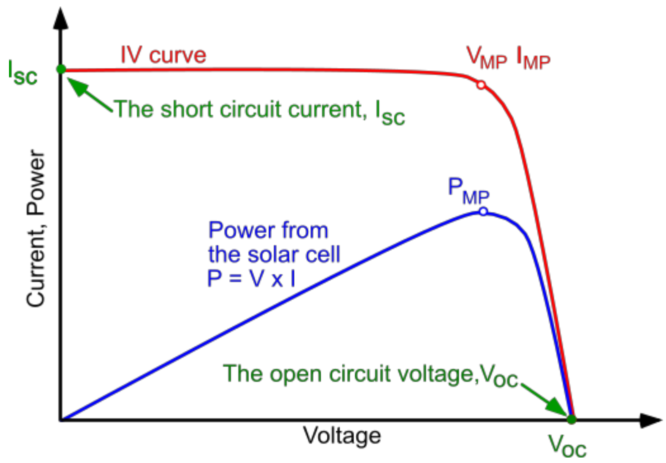


Figure 2.24 J-V Curve and Power curve of generic Photovoltaic cell indicating open circuit voltage, short circuit current and the maximum power point (MP) of operation [46]

The conversion efficiency can be expressed as the maximum power P_{MP} over the power of the irradiation incident on the cell area.

$$\eta = \frac{P_{max}}{I_{in}} = \frac{J_{sc}V_{oc}FF}{I_{in}} = \frac{J_{MP}V_{MP}}{I_{in}} \tag{2.7}$$

On a module level, there is a difference between aperture area efficiency (active area of module) and module efficiency (active and non-active area). The aperture efficiency would be higher than the module efficiency, also since non-uniform heating or illumination of a PV module can lead to reduction in power output and thus the module efficiency.

Different types of solar cell technologies use the photovoltaic effect, and as such different types of PV modules or designs are available. Indicating the performance by characterization of the mentioned parameters can assist in selection of technology. The most commonly used or most matured technology is that of mono or poly crystalline silicon wafer-based cells. This type of cell has a relatively high efficiency (21.2-27.6% [47]) depending on the sort of crystalline wafers, high lifetime, stability during operation and reliable power generation. Thin-film solar cells have slightly lower efficiencies (14-23.3% [47]) meaning a larger surface area would be needed to attain similar power outputs, or an equal area would have a lower capacity. Mono-crystalline silicon solar cells have higher efficiencies and are thus rated at higher nominal peak power than poly-crystalline solar cells, at constant surface area.

Industry standards can give 72 or 60 cell PV modules, of which the efficiency is given as the ratio of the nominal power output over the solar power input, or the irradiation of the entire module surface area (including dead zones). A 255 [W_p] mono crystalline PV module can have the same power output as a 255 [W_p] poly crystalline module but can differ in price, just as a 310 [W_p] 72 cell 1.94 [m_2] module can have the same efficiency as a 260 [Wp] 60 cell 1.63 [m_2] module [44]. For PV system design it is thus important to identify the (limited) available area, the necessary capacity and the efficiency of the modules to choose between technologies.

Prices for PV modules are given in [$/k$W_p$]. In general, the price for poly crystalline modules is lower and gives a better economic value for PV system application. Only when area limitations and power maximization requirements are more important would a mono-crystalline or other high efficiency technology be advantageous [44]. A graphical representation of different photovoltaic technologies and their efficiency values over time is given in Appendix B, to illustrate the trend in research and development and give a comparative price quality value indicating that higher efficiency and more complex cell structures are often accompanied by higher prices.

Factors affecting the irradiation incident on a solar module include the module's orientation, tilt and evidently the sun's position over time. The actual performance of a PV module at location can then be expresses as the output power compared to the input power in terms of irradiation incident on the surface area of the module. The performance ratio (PR) gives this ratio of the energy yield of a PV module (or system) over the input irradiance on the surface area of a whole module (or PV system). It incorporates all losses of the PV module or system itself including the losses of the additional components in the PV system (balance of systems) [44]. The PR is given by:

$$PR = \frac{PV\ yield}{Incident\ solar\ irradiation\ \cdot\ Surface\ area\ \ \cdot PV\ module\ efficiency\ at\ STC} \tag{2.8}$$

PR values can differ in warmer and cooler areas due to the temperature effect on the PV module efficiency. To give a yearly energy output estimation a simulation should be made of a PV system using actual (hourly average) location dependent irradiation data. Irradiation data sets are constructed using 20 or 30-year average values of irradiation and temperature data collected from several meteorological stations [44]. By specifying the input tilt angle, orientation and module specifications the output power can be calculated (PV Sol). For a longer (20 year) energy projection the degradation of the PV modules should be included. For Silicon type PV modules, a degradation rate of 0.5% per year is used [48]. The solar PV modules that are used by WEG will use the same value.

Another important factor is the fabrication quality of the PV module to ensure a 25-year lifetime. PV modules are tested for temperature changes (day, night, winter, summer), mechanical stresses (wind, snow, hail) airborne agents (sand, dust, salt), moisture (rain, dew, frost) humidity (atmospheric) and effects of high energetic UV irradiation on the material composition. This is equally important to prognose system degradation over a 25-year lifetime [45].

2.4.3.2 Balance of systems

The conversion efficiency of irradiation energy to electrical energy is not only reliant on the PV module characteristics and positioning. Minimizing losses in the PV system is equally important and depends on the choice and selection of the additional components within a PV system. The total of all other components within the system (excluding PV modules) is called the balance of systems (BoS). Within the BoS the following components are included [45].

Mounting structure

A mounting structure is needed to fix the PV modules in their respective array configuration, tilt angle and orientation. It provides structural stability from mechanical stresses and environmental effects like wind. Multiple mounting structure types are available for different kinds of surfaces, angles, environmental conditions. Also moving structures that enable solar tracking can be useful to increase effective incident irradiation.

Energy storage

Stand-alone RE systems with intermittent energy generation require an energy storage component. The most commonly used electrical energy storage (EES) technology are batteries (or chemical storage). However, due to certain operational conditions or cost considerations other storage technologies might be more suitable depending on the application scale and duration of storage (residential vs industrial).

Inverters

Inverters are necessary to convert the DC current from the PV modules into AC power to supply AC load points. Or to convert DC current form the storage component into AC current or vice versa for battery charging. Inverters are selected for both their capacity at point of connection to the load, nominal AC power output, and their DC power input capacity at point of connection to the PV modules [44]. The inverter capacity depends on PV module peak DC power, since the actual production of PV modules will most likely be lower than the STC conditions. The ratio of nominal DC output of the PV modules and the nominal AC output of the inverter is called the inverter ratio. This ratio depends on the number of PV modules connected to each inverter and can vary slightly due to available area for installation, and string sizing. The ratio is usually between 1.1 and 1.3 and a ratio of 1.2 or higher can be considered as full utilization of the inverter capacity. Taking this into consideration a configuration for PV module connections and inverter types can be made with which an initial PV system energy yield calculation can be based. Generally, two types of inverters can be used. Central inverters which connect multiple strings of PV modules, have higher power ratings and are used for larger (PV) systems in which the PV arrays and modules have the same orientation, tilt and capacity, or string inverters which are available in different (smaller) capacities to be used in strings of different configuration, each with their own MPPT [44].

Charge controllers

These are used in stand-alone systems to manage the charging and discharging control of the batteries. Charge controllers prevent overcharging or excessive discharge below acceptable DoD levels. Some high-end charge controllers include a DC-DC converter to handle transition from fluctuating PV voltage to constant battery charging voltage. In some cases, charge controllers are included in the BESS.

Cables

Cables connect all the different components of the PV system and to load points. Their thickness must be chosen correctly to minimize resistive losses in the system. And to cope with the environmental conditions.

For proper PV system performance assessment, the entire system should be taken into consideration (PV Sol) to calculate actual grid-ready electrical power generation and necessary energy supply.

2.4.3.3 PV module specifications and cost

WEG uses "Trinasolar" modules for their current and future projects. The specification sheet has been added in Appendix C, and a concise overview is given in Table 2.12. The performance and applicability of this of modules has been checked during the design and balancing of previous systems and is always considered in the design of any new project [49]. WEG hold a (turn-key) cost of 1150 [$/kW$_P$] for this type of module in their project, which will also be used in any assessment of this study.

Table 2.12 Trinasolar PV module specifications, used for WEG projects. [50] [51]

Specifications (Under STC)	**TRINASOLAR Honey-TSM-PD05**
Open Circuit Voltage V_{OC} (V)	38.3
Short Circuit Current I_{SC} (A)	9,49
Maximum Power Point Voltage V_{mpp} (V)	31,6
Maximum Power Point Current I_{mpp}(A)	9,02
Efficiency (%)	17,4
Normal Operation Conditions Temperature NOCT (°C)	41 +/- 3
Size (mm)	1650 x 992 x 35
Number of cells	60

2.4.4 Diesel generators

Diesel fueled generators (Genset) are considered a mature technology and are implemented in a large variety of systems and applications. The combustion engine principles will not be explained here, yet a short schematic of the electrical energy generation process is given in Figure 2.25.

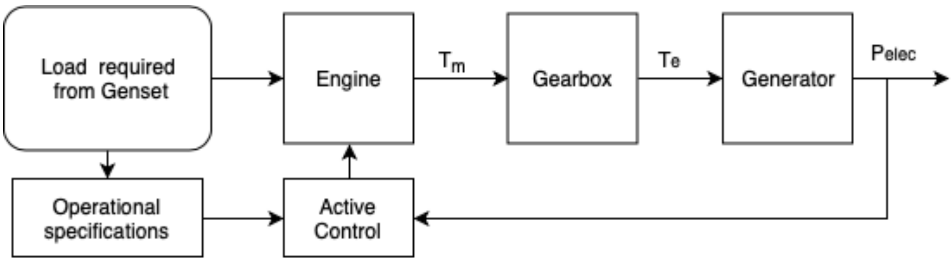


Figure 2.25 Diesel generator elements with active control for determination of output power in relation to timestep load and production

As can be seen, the diesel controller takes into account its current operating level, the required load and the operational limitations or requirements. It then scales the power output or in case of multiple Gensets decides to activate or shut down additional units. Important influential factors on the operational efficiency of a generator are the fuel consumption, mechanical and electrical efficiency. Most generators used for energy systems have specified operating conditions influencing the flexibility in an energy system. Some relevant considerations for generator sizing used by WEG are:

- *Genset capacity (at 40% operation) <= Estimated min load.*
  Meaning that at 40% operational capacity a GenSet should be able to cover the estimated minimum load requirement.
- *Genset capacity (at 100% operation) >= Estimated max load.*
  Meaning that at maximum capacity the GenSet should be able to cover the maximum estimated load requirement

This lower limit of 40% is set due to the efficiency decrease and fuel consumption increase of the Genset at lower operational capacities [5]. WEG uses two types of Gensets, the *'Caterpillar C7.1 120 kW'*, and the *'Caterpillar C9 180 kW'* to provide more flexibility in installed capacity and deployment strategies. As a generator is relatively easily activated or deactivated, with short start-up and shut-down times it can be considered a fully controllable capacity, providing a reliable base-load generation capacity to supplement any intermittent renewable source or to function as a backup. Within WEG this dependable capacity is sized to account for the full peak power demand of a project. However, its operational time and energy share in the energy mix is reduced by introduction of solar PV generation combined with a BESS. It functions thus solely as an addition to the preferred renewable energy generation and only operates when the renewable fraction does not satisfy the demand. In order to extend operational lifetime, lower possibility of failure and prevent overcapacity multiple combinations of different size generators can be used. In this research the

GenSet is only used in a baseline evaluation of a conventional hybrid system, to create a reference of technical performance, and is considered the component that is to be removed or replaced in a fully renewable hybrid system. To quantify the fuel consumption a consumption per generated kWh is used of 0.28 [Liters/kWh]. This is then used to calculate the required amount of fuel and the accompanying fuel and operational costs.

2.4.4.1 Generator sizing considerations

WEG sizes its diesel generation capacity to cover the entire peak demand, thus providing 100% reliability of a system. Multiple generators are used instead of a single generator using the above considerations. Using multiple generators creates another advantage for alternating maintenance and operation reducing downtime and increasing reliability of the entire system in case of GenSet failure.

Important to notice is the energy share of diesel generated energy over the system lifetime. As the generated energy of PV decreases over time, and the load demand increases, the required energy from the GenSet will increase, placing a higher load on this generation component towards the end of its lifetime. Sequential installment of generation capacity is thus preferred, adding generation capacity in later stages of the system operational lifetime to ensure reliability and prevent overcapacity in early stages.

In hybrid systems, based on a worst-case scenario, The GenSets should be able to cover the total energy demand, in case of low solar PV availability and BESS capacity. A relatively low CAPEX compared to other renewable sources increases the attractiveness of this component in a hybrid system. However, arguments can be made for the higher Operational expenses (OPEX) related to its fuel consumption, and the impact of such generation on health, safety and environment.

2.4.5 Storage systems

2.4.5.1 BESS key terminology

To classify the performance and operation of a battery energy storage technology some key indicators can be used. The capacity of a battery is given in the ampere-hours (Ah) at a certain discharge voltage. This represents the amount of energy contained in the electrochemical storage. The Ah is the discharge current delivered in a specified time.

Since batteries have different composition, sizes and chemicals, it is necessary to quantify this capacity in comparable values. For this the energy densities can be used. In particular the gravimetric and volumetric energy densities. These indicate the loading capability of a battery made for higher specific power and reduced specific energy (e.g. power tools or cell phone batteries). The C-rate of a battery indicates the speed at which a battery is discharged or charged. At 1C the battery charges at a current as specified in its normal (market) Ah rating. A 0.5C rating would indicate half this current and double chare/discharge time and similarly 2C would indicate a double nominal rated current and halving of the time.

The load required from the battery is the current drawn from the battery pack in a specific time. A reduction of charge and internal battery resistance at some point create a voltage drop under the required load, also defined as the lower DoD limit, or end of discharge. The power delivered is denoted in Watts (W) and the energy during this discharge time in Watt hours (Wh) [52].

In order to quantify a price performance value, the cost per kWh is used ($/kWh). This gives a price indication for the capacity that is installed either in power or energy.

2.4.5.2 BESS selection

Various storage options are available for long- and short-term applications. This can be in the form of potential energy storage (flywheels, pumped hydro), chemical compounds/fuel storage (hydrogen, biofuels) or electrochemical storage (batteries) among others. Reliability in a fully renewable system is largely dependent on the integration and performance of the storage component. The intermittent nature of renewable energy sources requires an (B)ESS to compensate any fluctuations. Since a grid connection or a fully controllable and dependable secondary generation component is absent in this FRES configuration, the complementary function needs to be instantaneous and of sufficient power for a specified duration. The electrochemical storage options are the most suitable (modular) for this.

The different options of battery energy storage systems (BESS) each have their advantages and disadvantage related to their power or energy densities, cycle life, depth of discharge and operational conditions. Because of this a consideration needs to be made which type can be used for this particular system. The storage capacity is used on a daily base, with several hours of continuous discharge at a time. Since high energy values are needed a deeper discharge is required to maximize utilization of the battery capacity and its ability to provide energy. However, a larger DoD is directly related to a shorter battery lifetime. Since batteries are relatively expensive, its cycle life is of importance to the entire system cost. It is preferred to replace the batteries as little as possible. The application for rural areas also makes the choice between battery types limited since some that might meet the requirements are too expensive.

Multiple types of BESS are commercially available each with their own (dis-) advantages. An overview of battery storage technologies is given in Figure 2.26.

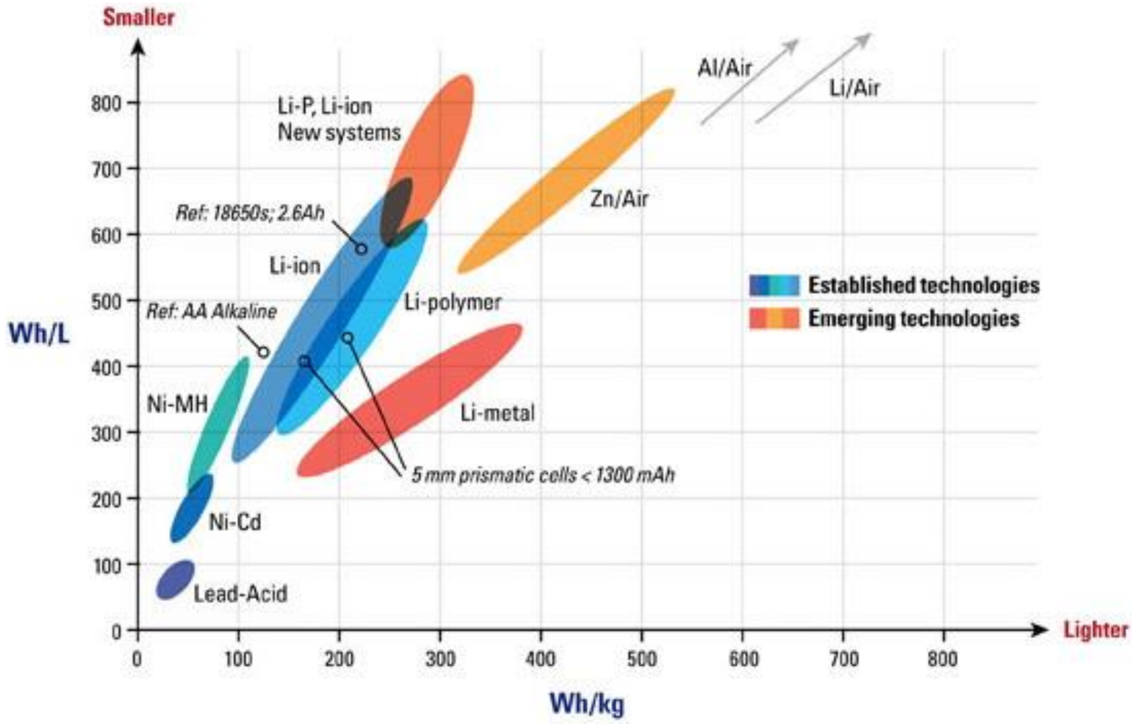


Figure 2.26 Gravimetric and volumetric energy densities for emerging and established battery technologies indicating applicability for energy system applications [53]

As can be seen, among the established technologies, Li-ion type battery storage has the highest volumetric energy density and second highest gravimetric energy density. Combined with its large market share and rapid increase in usage in the last decade this would form a suitable battery type for integration in hybrid systems. Lower costs are expected in the future together with an increase in efficiency. Another commonly used and mature battery technology is the deep cycle Lead-acid battery. It can be seen that the energy density values are lower compared to almost all other technologies, yet its affordability and diversity in application makes it an option for energy systems. Some advantages and disadvantage of both technologies have been listed in Table 2.13.

Table 2.13 Advantages and disadvantages of Li-ion and Lead-acid battery types [52]

Type	**Li-ion**	**Deep cycle Lead-acid**
Advantages	- High specific energy and high load capabilities with Power Cells. - Long cycle and extended shelf-life; maintenance-free. - High capacity, low internal resistance, good coulombic efficiency - Simple charge algorithm and reasonably short charge times - Low self-discharge	- Inexpensive and simple to manufacture; low cost per watt-hour - Low self-discharge; lowest among rechargeable batteries - High specific power, capable of high discharge currents - Good low and high temperature performance
Disadvantages	- Requires protection circuit to prevent thermal runaway if stressed. - Degrades at high temperature and when stored at high voltage - No rapid charge possible at freezing temperatures (<0°C) - Transportation regulations required when shipping in larger quantities	- Low specific energy; poor weight-to-energy ratio - Slow charge; fully saturated charge takes 14-16 hours - Must be stored in charged condition to prevent sulfation. - Limited cycle life; repeated deep-cycling reduces battery life - Flooded version requires watering maintenance - Transportation restrictions on the flooded type - Less environmentally friendly

A comparison is made in Figure 2.27 between the depth of discharge (DoD) and cycle life of deep cycle lead-acid and Li-ion (LiFePO4) type batteries. As can be seen, at a DoD of 80% the charge/discharge quantity of Li-ion is significantly higher than that of deep-cycle lead-acid batteries (or AMG lead acid).

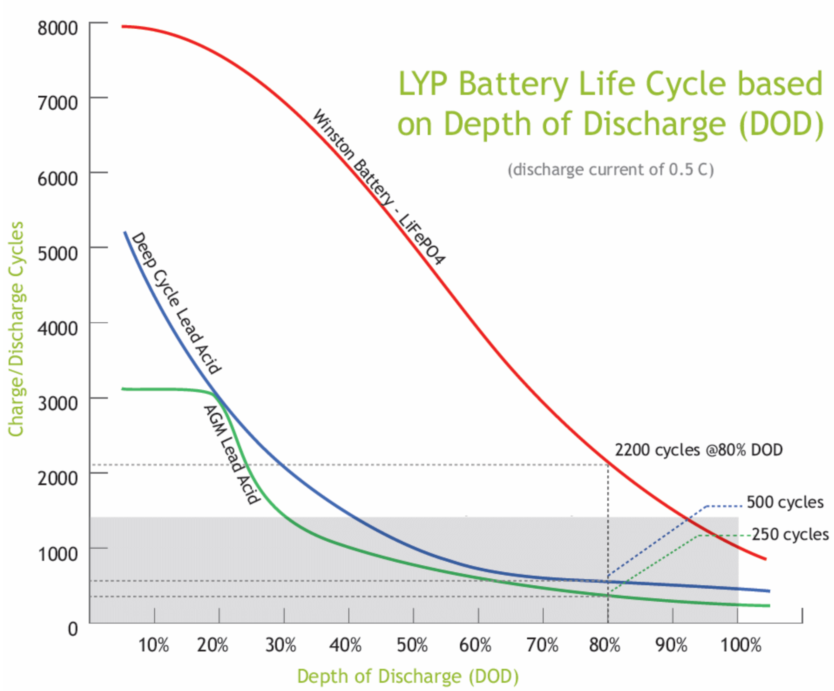


Figure 2.27 Cycle life vs DoD of Lead-acid and Li-ion battery types [67]

So even though Lead-acid batteries might be a more mature and cheaper technology, their replacement frequency combined with higher maintenance requirements can become an unwanted investment over a 20-year system lifetime. This is not the preferred choice. The battery type with the current highest market share [52] and application diversity is that of Li-ion. With its higher cycle life, and correlated DoD value, operating conditions and higher energy density than Lead-acid (Figure 2.26) it forms a viable option for the BESS in a FRES.

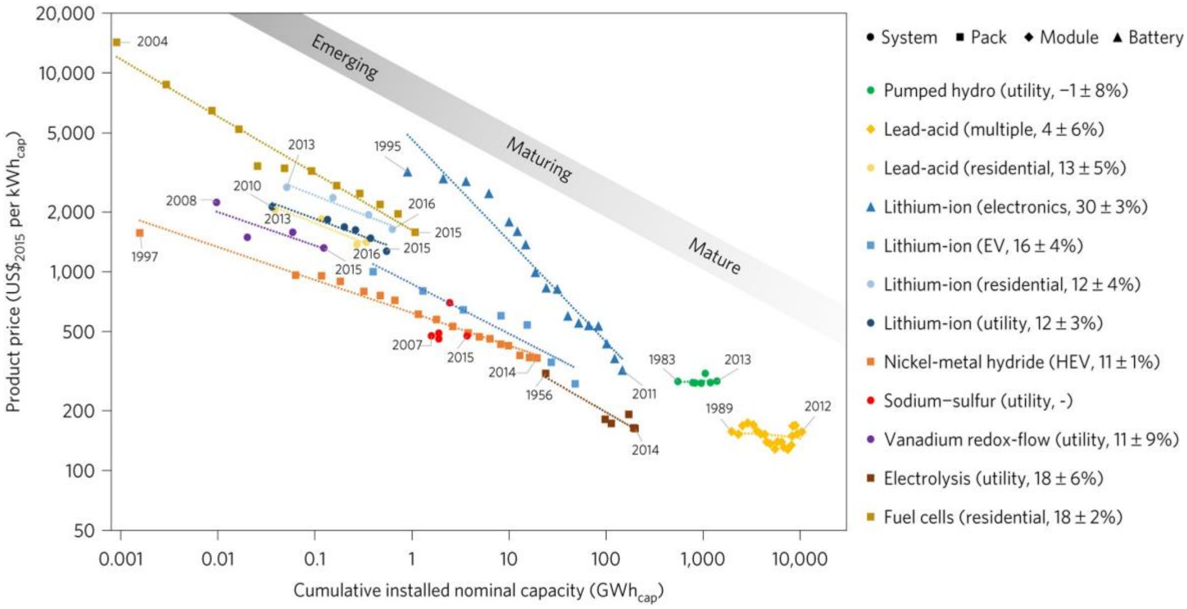


Figure 2.28 Production cost trends of battery types per sector and cumulative installed nominal capacity [54]

As can be seen in Figure 2.28, with increased installed capacity of Li-ion (EV, residential, utility), and other battery storage technologies, the cost shows a decreasing trend in almost all sectors of application. Based on both the technical and prospective advantages of Li-ion compared to lead-acid or other technologies like Nickel metal hydrides, WEG used Li-ion battery packs for its BESS. TESLA has developed a turn-key BESS specifically designed for larger scale projects and industrial applications. The Tesla "Powerpack" has been used in WEG's flagship project the "Sabang Project" located in Barangay Cabayugan, Puerto Princesa, Palawan, The Philippines, featuring a 2.3 MWh TESLA powerpack system [44]. Due to the experience gained from this BESS installation, and continuing cooperation with TESLA, this study will consider the powerpack as the BESS to be used in any FRES simulations. Table 2.14 provides a summarized overview of the specifications. The specification sheet can be found in Appendix D. WEG holds a turnkey cost value of 575 [$/kWh] in their projects, which will be used for this feasibility study as well.

Table 2.14 TESLA Powerpack specifications [55]

TESLA Powerpack: Bi-directional inverter and DC power packs	
Powerpack Area requirements	50 [kW] / 95 [kWh]: 8.9m 2 100 [kW] / 190 [kWh]: 11.8m2 250 [kW] / 475 [kWh]: 20.5m 2 500 [kW] / 950 [kWh]: 35m2
System size (modular)	50-500 [kW]
Continuous power duration	2 hours
Operating ambient temperature	-30 to 50 [°C]
Roundtrip efficiency @ C/2	87 [%]

Figure 2.29 TESLA powerpack modules with inverter [55]

3

Method

The feasibility assessment framework constructed for this research and the role and content of its individual elements, including the key performance indicators that will be used to analyze the hybrid energy system in section 3.1. Section 3.2 will elaborate on the modeling tools and their related optimization strategies that are used in this assessment. Section 3.3 will describe any system losses as included in the models, followed by the assumptions made with regard to the energy system, the operational conditions and the simulations in section 3.4.

3.1 Solar PV - Tidal Stream - BESS hybrid energy system feasibility framework

The flowchart made for techno-economic analysis of (PV-TS-BESS) hybrid energy systems can be seen in Figure 3.1, reflecting the process from initial sourcing to system feasibility assessment through multiple stages, cost and reliability comparison and optimization of some of the relevant performance parameters. Generally, hybrid energy systems feasibility assessment uses an order from renewable energy source (RES) potential analysis, yield calculations and load profiling, simulation and optimization to system design parameters [19]. This general order of steps has been used to create a more adapted flowchart for the assessment of tidal stream energy implementation and reflects the steps that will be taken throughout this study. The following subsections will describe the individual elements.

3.1.1 Block A: Location and RES potential assessment

Before designing any energy system, it is important to investigate the project site. Every system can be different, and it is most cost and energy efficient to tune the design to the target environment rather than designing a multipurpose single size system. Modularity or flexibility in design is one of the requirements and characteristics of these FRES, giving it its advantage over less scalable/adaptable (centralized) energy sources. The site assessment consists of multiple factors described below.

Demographic scaling

It is important to gather information on the size of the population for system sizing purposes. This information can be attained either by acquiring governmental statistical data or via third party organizations. Another method would be to produce this data during a site visit in cooperation with the local municipality or use experience data and monitoring for estimates.

Economic activity

Energy use can be significantly influenced by the amount and type of economic activities. Fishing industry/ pearl farms/ agricultural activities/ hotels and resorts each have their own specific energy. It is assumed that the growth of economic activities is parallel to any growth in energy use by the residential sector, since in the case of rural islands it is mostly the local population that works in and uses any facilities. Proper assessment of the residential, industrial and municipal facilities is essential to construct a load profile of an island.

Geographical characteristics.

Geographical conditions can influence both resource potential and accessibility. The location of a site can determine the intensity and periods of resource availability (irradiation, tides). Any special necessities for transport or maintenance of equipment could then be included in cost considerations and planning. Land availability and topography for wind turbines or PV systems is important for trade-off between decentralized installation in the local infrastructure or localized installations. Additionally, seabed profiling (bathymetry) is essential for determining tidal energy potential.

Weather conditions

Weather conditions can be studied in order to identify any influence they might have on the RES potential or operational conditions. Any specific weather-related energy consumption can be included in load profiles. For example, high temperatures can cause more use of refrigeration or air-conditioning units, which have fairly high-power consumption levels. Furthermore, daylight timing and accompanying energy use influences the load demand. Apart from the load profiles it is important to incorporate any natural phenomenon or special weather conditions into the design considerations. Areas with limited or no rainfall could need more maintenance (cleaning) for PV modules. High rainfall or wind speeds require structural adaptations to any components and can influence deployment safety of for example tidal stream turbines. High ambient temperatures might also require climate control for BESS.

Municipal or governmental legislation

Knowing the legislative or municipal requirements and restrictions can influence the choice and sizing of RES. Land availability for PV, permission to operate within fishing waters for tidal turbines, protected area's that cannot be used or that need permits to operate within are of influence. Land ownership of the local community can make it difficult to acquire enough land (centralized or decentralized) to build a hybrid system, this land might be used for economic agricultural activities, personal sustenance, or might have traditional cultural value. These restrictions can affect the design of any system.

RES selection and potential calculation

Conservative calculations on the energy availability can indicate the most promising RES. If any requirements for RES implementation are not met, it would be either technically challenging or financially unbeneficial to pursue its implementation. Simply knowing how much energy is available does not mean this energy is accessible or convenient for implementation. This could be due to any of the above-mentioned factors or simply excessive distances between generation and load points adding cost or construction difficulties. Creating a proper sitemap will give reasoning to RES selection and system design. A sitemap can be constructed in a number of ways such as using existing infrastructural blueprints, satellite images or drone images combined with a mapping of the island itself. Expansions of neighbourhoods or industry does not always follow strict administrative procedure, meaning any available maps might be out of date or incomplete.

3.1.2 Block B: Generation potential calculation

Satellite data and/or extrapolated data can provide with the necessary insights to categorize any RE potential. However, in the case of remote islands this data is not always available, creating necessity for local measurements. For solar PV more general assumption can be taken that the behaviour will be close to that observed in similar locations. For Tidal stream, similarly to offshore wind, the conditions can differ on a smaller scale in otherwise equally classified areas or climates. Some locations might already have electricity grids in place. These systems are either not producing enough energy to supply the entire community or only during limited time periods due to insufficient capacity or fuel. It is important to analyse these systems to assess if parts of the grid or generation components (Diesel generators / PV modules) could be incorporated into the new system.

3.1.3 Block C: Categorial load profiling and estimation

The required energy and power must be quantified for any energy system. There are multiple ways to collect necessary data to construct both load profiles (daily, monthly, seasonally) and to identify the system boundaries such as the minimum required power, peak load and the system lifetime. Load point classification or energy use data can be used for this, including both current demand and any demand growth projections.

3.1.4 Block D: Configuration sizing and optimization strategy

In order to quantify the installed generation capacity at the specified location, based on the load and RE potential, a simulation strategy is needed to enable stepwise adaptation of the components in relation to the performance indicators (e.g. renewable energy share, LCOE, LOL). Solar PV and tidal stream components are sized based on their peak power and energy yield in combination with BESS. Diesel, not being a renewable energy sources, does not have a resource dependent intermittent power curve but is included in the conventional assessment as dependable capacity. Only at a certain point can a relatively stable yet still intermittent source like tidal stream energy exclude the necessity of diesel by supplying an equal base load or peak load coverage in combination with BESS. A goal of FRES optimization should thus be to indicate what its power reliability is and if it is commercially viable to implement. The generation principles have been described in chapter 2. Each source has its specifics regarding minimum/maximum step size change, capacity, price-quantitative optimality and commercial options. This makes that for each source certain initial capacities can be set. Feedback from the actual generation can indicate the possibility for increase or decrease. A different strategy can be used for the initial sizing of the BESS, based on either required days of autonomy (DOA) or minimalization of cost/excess capacity. Quantifying the excess generation and the average energy shortage can give an indication of the initial viable battery capacity. In order to keep the storage component size small, and reduce cost, the targeted storage strategy for this a rural system should aim for effective demand coverage instead of a large DOA. Equally important to identifying the necessary storage capacity is the choice for storage technology (section 2.4.5) since this influence's factors like battery bank size, cost, and operation (maintenance, environment).

3.1.1 Block E: Peak power and energy requirement

Island wide energy demand over a predetermined period can be quantified using the load point classification and profiling. Time-step and seasonal fluctuations can be taken into account as well as the daily spread of energy demand. A yearly demand increase is included in the system lifetime simulations to account for expansion due to electrification status. An additional consideration should be made for the unleashed suppressed demand which is a higher energy increase rate due to the already existing potential for energy use of appliances, industry and expansion within current infrastructure. This is of effect in the first years after introducing reliable 24/7 power supply. After this initial growth the yearly energy demand growth can increase more moderately during the system lifetime. The peak load and energy demand values form the targeted operational requirements for the generation and storage components for each year.

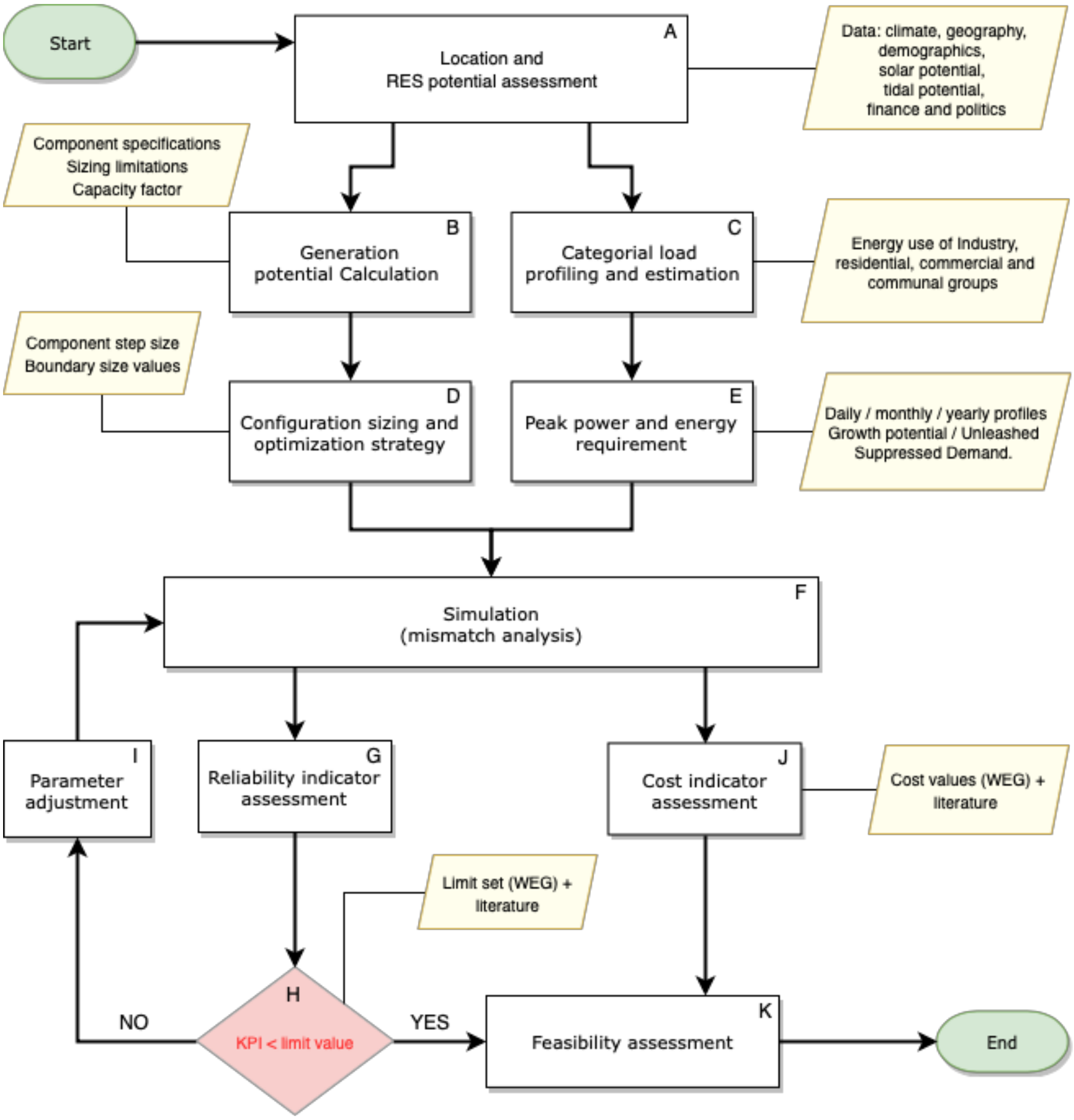


Figure 3.1 PV-TS-BESS FRES feasibility assessment flowchart reflecting the process rom initial assessment to system design parameter and multi-objective cost reliability assessment

3.1.2 Block F: Simulation

Using acquired irradiation and current velocity data together with the constructed load profile system and BESS specifications, simulations can be done. For the (initial) system configuration certain time periods and quantities of over/under-production can be identified as well as the frequency occurrence. This mismatch forms the base for adjustment of configurations. It can also indicate which generation component is cause of any mismatch, how the individual components perform and how these can be adjusted accordingly. The strategies and indicators as discussed in section 2.2 can reflect the required considerations. An incremental change in any of the components has different effects on the cost and reliability. Important is to gain insight in the response of a system to its variables and identify those who influence the system the most. Ideally a variable should positively affect both the technical and financial aspects, meaning an increase of reliability with a decrease or relatively smaller increase of cost. From the simulations the evolution of the performance indicators with every incremental step change can be analysed.

3.1.3 Block G: Reliability performance indicators

As discussed, the performance of a system indicates its reliability in providing sufficient energy at the time of demand, thus its efficiency in effective energy generation. Multiple performance indicators can be used. For a FREs of this type the Loss of load (LOL) and loss of load hours (LOLH) are used to investigate the energy coverage and identify the frequency of shortages. The own consumption of a system will indicate the efficiency of a system's effective generation to prevent oversizing and decide if a system, even if optimized, could actually be realistically considered. The generated energy of the system is represented as follows:

$$E_{gen} = \sum_{t=1}^{T} (E_{PV,t} + E_{TS,t}) \tag{3.1}$$

Where E_{gen} represents the total combined energy of the solar PV and tidal stream components E_{PV} and E_{TS} respectively for a specified time period T (hr). The effective energy is given by:

$$E_{eff} = \sum_{t=1}^{T} (E_{PV,t} + E_{TS,t} + E_{BESS,t}) \tag{3.2}$$

E_{eff} is the total energy used for load satisfaction including the energy of the BESS, E_{BESS} . The reliability indicators are then represented in the following way:

$$LOL = \sum\nolimits_{t=1}^{T} (E_{eff,t} - E_{demand,t}) \tag{3.3}$$

With $E_{demand,t}$ the demand at timestep t and:

$$LOLH = \sum\nolimits_{t=1}^{T} F_t \tag{3.4}$$

$$F_t = \begin{cases} 1 \; if \; E_{eff,t} < E_{demand,t} \\ 0 \; if \; E_{eff,t} \geq E_{demand,t} \end{cases} \tag{3.5}$$

Where F_i is a function of the generation and demand providing a value for the amount of power shortages within the time period T. A distinction should be made between the systems failed supply of energy and the excess energy which is generated but not stored in the batteries nor used for load satisfaction [45]. This is represented by the own consumption rate. The own consumption (OC) rate is calculated with:

$$OC = \frac{\sum_{t=1}^{T} E_{eff,t}}{\sum_{t=1}^{T} E_{gen,t}} \tag{3.6}$$

Any additional energy generation factor would be included within the brackets in equation (3.1). At a fixed or constant LOL/LOLH the generation component size, or number of generation units of both PV and tidal, non-linearly change with the number of storage units. The goal can be to determine the right number of generation units in combination with storage units that provides the required performance and have the lowest combined system cost [22].

3.1.4 Block H: LOL / LOLH limit

Reliability limit indicators need to be set at an appropriate value to compare the performance of different configurations. The LOL rate lies between 0 and 1, with 1 indicating no energy delivery to the demand side and 0 indicating no shortage of energy supply and can be given in a percentage of total energy demand. In general, the lower the value of the LOL the more reliable the system is. As an example, an LOL of 0.01 would imply that during a 24-hour load cycle with a daily demand of 6919 kWh there is an acceptable shortage of 0.01 *6919 [kWh] = 69.19 [kWh] (or 1 % of daily demand). This value is more representative on a yearly time period since this includes any daily, seasonal fluctuations in demand a generation and gives a more enveloping idea of load satisfaction. The LOLH for the above example can vary significantly since it does not quantify the energy shortage, but the frequency of shortage which is defined by any amount of unmet load in an hourly timestep e.g. the shortage of 69.19 kWh could be within 1 hour or spread over 10 hours of varying amounts.

To determine an acceptable LOL and LOLH the following criteria regarding technical and social consequences of loss of power supply can be taken into account:

- Type of load point (hospitals vs domestic): prioritize for severity of consequence of power loss.
- Time of day: for residential power supply it is often more acceptable during the night, when activity is at its lowest than during the day.
- Scale of energy shortage: there is a difference between a power loss influencing a city or a village.
- Economic activity: if it is dependent on the reliability of power supply, any disruption could have major financial or industrial consequences depending on type of activity (conserving food vs lighting for an advertisement)

Advised values are given for several applications of 0.1% for domestic illumination, 1% for appliances and 0.001% for telecommunication, however these are generalized values and not customized for rural electrification conditions, meaning that reliability values can show differently for rural applications compared to urban power usage [45]. For sensitivity purposes the effect of multiple LOL values on component sizing and energy generation can be assessed [22].

3.1.5 Block I: Parameter changes

This step represents the stepwise change in the input variables or parameters of the simulations, including the multiple scenarios considered in an optimization. If a reliability value is not met, the related costs for the configuration do not have to be considered since the priority function of the system is to provide energy within the reliability boundaries. The values and ranges can be set depending on the requirements and considerations made in the preceding steps of the assessment. However, for purpose of this study no sizing limitations are set for the components based on available land area or funding limitations.

3.1.6 Block J: Cost performance indicators

When a configuration is technically feasible, the LCOE and other cost parameters can be assessed. Each configuration is with its own cost due to differences in CAPEX and OPEX of the component's configurations and their effective energy use. For a system cost analysis, the most used indicator is the Levelized Cost of Energy (LCOE) due to its enveloping nature. Next to this a comparison can be made between the net present costs of the configurations. The Net Present Cost (NPC) [19] is expressed by:

$$NPC = \sum_{n=1}^{lifetime} NPC_n = \sum_{n=1}^{lifetime} \left(N_{PV} * C_{tot,pv} + N_{tur} * C_{tot,T} + N_{batt} * C_{tot,BESS} + C_{inv} - SV\right) \quad (3.7)$$

$$C_{tot} = C_{cap} + C_{op} + C_{rep} \tag{3.8}$$

Where N_{PV} , N_{tur} N_{batt} are the number or size of each component and C_{tot} their respective price consisting of the capital investment C_{cap}, operational expenses C_{op} and replacement cost C_{rep}. Any additional initial investment cost (grid, powerhouse) are given by C_{inv} with SV the salvage value after decommissioning, with n denoting the respective year of the expense. The expenses are discounted to include the time value of money in relation to the interest and inflation rates using the discount factor:

$$f_d = \frac{1}{(1+i)^n} \tag{3.9}$$

The discount factor f_d is a function of the discount rate i and the respective year in the project lifetime represented by n. The LCOE can be calculated as follows [44]:

$$LCOE = \frac{\sum_{n=1}^{T} \frac{(I_c + O\&M + F_c)}{(1+i)^n}}{\sum_{n=1}^{T} \frac{E_{eff}}{(1+i)^n}} \tag{3.10}$$

With the discounted values of the total investment cost I_c, operation and management cost O&M, fuel costs F_c and the discounted total effective generation E_{eff}. The unit of LCOE (cost/kWh) expresses the cost per energy value over the entire project lifetime taking into account the time value of money providing an indicator that measures the competitiveness of a system, as is not necessarily the case with the NPC which only includes the cost and not the accompanied effective energy generation e.g. a system with lower I_c might not be more efficient in energy generation per kWh (high diesel fuel cost compared to lower OPEX of solar PV).

For this study no implementation of any profit calculations, payback time or company specific financial models are included. It is aimed at providing a comparable performance indicator to locate an optimal configuration and conclude on its feasibility in relation to conventional hybrid systems and can be used as an indication of minimal break-even selling price. However, since the individual component costs are of great influence on the economic feasibility some sensitivity cases can be included in the optimization to analyse the systems sensitivity to external cost changes or express preference for certain configuration strategies. The preferred strategy here is to increase the capacity of the cheapest generation source first in order to lower any capacity shortages. Following from the cost considerations in section 2.4 the order of increase would be first solar PV followed by Tidal stream and BESS taking into consideration that any increase in generation capacity does not directly increase the effective consumption of energy and could require an increase of BESS to increase dependable capacity and effective energy consumption.

3.1.7 Block K: Feasibility assessment

Finally, to classify a configuration for its technical and commercial feasibility the combination of the key performance indicators allows to filter between all results. Studying the response of the LOL / LOLH and LCOE to changes in the variables allows to perform some simulations for aimed configurations. Any excessive operation can be assessed by looking at the multiple indicator values. Cost reduction can be done by reducing the share of the most expensive component either in CAPEX or OPEX, or increasing their effectiveness, by for example segmented instalment of generation capacity and active control of tidal turbines. However, these options are not within the scope of this feasibility assessment.

A graphical representation of installed capacity and performance indicators can be made comparing different scenarios and configurations. Also, this would enable a quick comparison between systems for different locations or to identify certain design limits exclude certain configurations. However, in order to do a thorough optimization, it is not sufficient to find one configuration that satisfies the requirements, multiple configurations and scenarios can result in an acceptable performance. Optimization is necessary to find those that have the best possible combination of reliability and cost values. For this software like HOMER-pro can be used which assesses all possible combinations in a more thorough optimization process and gives all possible combinations that could satisfy the load requirements. Some configurations do not have to be included in the configuration matrices due to insufficient or excessive sizing or illogical utilization of available sources/components (BESS only or PV only).

In order to extract more general observations and to be able to better assess the feasibility of fully renewable energy systems in other locations sensitivity studies can be performed and correlations of the optimization can be generalized. This is necessary since the optimization and feasibility assessment will be done for a very specific set of conditions for a single location in this study. In this study the following sensitivity studies will be done:

- Cost sensitivity of tidal stream cost per installed capacity
- Reliability constraint changes (LOL limits variation).

The prime objective of the optimization could be to minimize storage bank size, maximize profit, prioritize energy reliability over cost, reduce excess generation, or determine energy mix shares [19]. For rural island applications however, a best compromise solution needs to be found between system reliability and system cost [56]. After this described assessment is made, factors that lie outside of this optimization scope can then be included for decision making, such as supply chain considerations or legislative requirements, land and ocean area availability, and off course (financial) risk considerations. A summarized description of the flowchart elements is given in Table 3.1.

Table 3.1 Feasibility flowchart block description summary [21] [9] [19]

Block	Block name	Description
A	Location and RES potential assessment	The condition of the targeted site needs to be assessed (location, environment, accessibility). The available energy sources need to be identified by their accessibility, availability and the most suitable sources can be selected for further analysis.
B	Generation potential calculation	Quick analysis of the generation potential can be made using insolation, current, windspeed or other required data, if no data is available then data can be acquired in the following ways: Data acquisition through reliable sources (software/weather stations/governmental) Synthetic data production using adjacent locations Data through measurements at location (preferred option for rural locations)
C	Categorial load estimation and profiling	The expected load profile and energy demand growth/fluctuations need to be made, using either the historical data, measurement equipment or experience data and site assessments.
D	Optimization strategy and initial component sizing	The different RES have different generation profiles that need to be combined in order to identify gaps in production or overproduction. By analysing the load profile and the generation potential the required initial size of each component can be estimated, or certain ranges can be excluded from the simulation.
E	Peak power and energy demand calculation	From the load profiling the entire system energy demand over a predetermined period can be quantified.
F	Simulation	Software tools are used to systematically simulate the system behaviour and functionality of all components over the system lifetime. This will lead to a result matrix of the required performance indicators. Multiple tools are used for purposes of optimization and insight in the system response.
G	LOL/LOLH calculation	From the simulation results the values for LOL and LOLH can be deducted and give feedback on the progress of simulation and optimization to exclude or increase the search range until suitable configuration are found.
H	Reliability limit check	Only when a configuration meets the required reliability values can it be considered an acceptable system configuration and is it useful to continue include it in the financial analysis.
I	Parameter adjustment	If within the configuration matrix there are no acceptable configuration, the parameters of the simulation or optimization can be adjusted. This can include sensitivity analysis, search range adjustments and exclusion of unrealistic configurations.
J	LCOE calculation	For the LCOE calculation both the cost factors and performance factors are needed, which can be extracted from the simulation results.
K	Feasibility assessment and sensitivity analysis	Comparing both technical and financial performance indicators and studying the sensitivity of the system to certain variables/parameters can lead to general conclusion about the techno-economic feasibility of tidal stream implementation in hybrid systems and a more specific conclusion about the implementation or the project of a particular case study.

3.2 Modelling tools

A technical and financial feasibility analysis of a fully renewable hybrid system compared to a conventional PV-diesel hybrid system requires multi-year simulations. For this an inhouse (Excel based) models and the HOMER-pro software for energy system optimization will be used. A conventional system will be taken as a baseline for system performance comparison and a feasibility perspective.

3.2.1 Tidal stream turbine model

Since no previous model for tidal stream turbine energy generation or calculations is available in WEG, a representative model was made. A description of the energy generation principles is given in section 2.4.2. Here a description of the model built in "Microsoft Excel" is given together with a short description of the considerations to be made for each step of the calculation process from current velocity to hourly energy yield. Table 3.2 shows the required input parameters and variables for tidal stream energy calculations. These values can vary between different turbines and locations and need to be specified for each project.

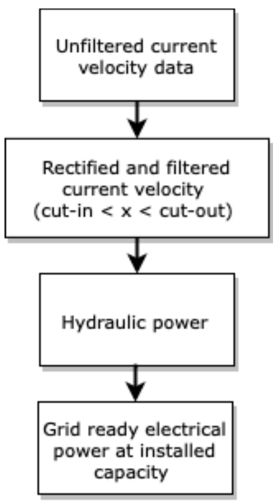


Figure 3.2 Block diagram of turbine energy yield calculations from current velocity dataset filtering

Table 3.2 Input variables and turbine specification values

Type	**unit**
Seawater density	[Kg/m3]
Weight	[Kg]
Minimal water depth	[m]
Nominal current speed	[m/s]
Turbine max power rating	[kW]
Cut-in current speed	[m/s]
Cut-out current speed	[m/s]
turbine efficiency (mechanical + electrical) (Cp)	[%]
Overall efficiency (mechanical + electrical + Betz limit)	[%]
Rotor diameter	[m]
Swept area A	[m2]
Installed capacity (kW)	[kW]

The nominal current speed, weight and rotor diameter can be used to assess if a turbine is suitable for installation in a targeted site or current range. An hourly current velocity dataset consists of (positive and negative) values denoting the change in direction of the current flow. Since bidirectional turbines or self-directional turbines are used the absolute values, or rectified set of data points, can be used to represent the current velocity in line with the turbine operational direction. The first step is thus to correct the velocity values to their absolute values in order to eliminate directional influences. Since each type of turbine operates between a specified range of current velocities described by the cut-in and cut-out values, the dataset can be filtered to eliminate the velocities that are outside of the operational range. This gives a dataset with effective values that can be used in the calculation for the hydraulic power that is available in the turbine head (equation (2.4). Since there is a maximum mechanical rating for tidal stream turbines the output power is limited to the turbine max power rating as given in its specifications. This value can then be corrected for any efficiency losses and subsequently gives the grid-ready electrical power at installed capacity (Figure 3.2). With equation (2.5), the turbine power can then be calculated. An increase in number of turbines is here assumed to multiply the hourly yield with the number of installed turbines. The hourly energy yield profile can then be used for multi-year combined energy simulations for the entire system.

3.2.2 Exhaustive search model

The excel model used for the exhaustive search (semi-simulated annealing) method was constructed by WEG and is here adapted for purposes of introducing tidal stream energy generation in the energy mix. Table 3.3 shows the possible input values of the fixed parameters, which are partially deducted from conventional hybrid system design considerations made for the case study of this research.

Table 3.3 WEG Excel based model input and output parameters for hybrid energy system simulation

Type input	unit	Type variable output	unit
Cable losses	[%] of generation	Yearly energy to be supplied	[kWh]
Hourly Power tidal	[kW]	Hourly energy to be supplied	[kWh]
Hourly Power PV (calculated with PV Sol)	[kW]	Hourly combined generation	[kW]
Hourly Combined available energy (after losses/inverter)	[kWh]	Own consumption of generation (with battery)	[kWh]
Hourly load + AC losses	[kWh]	Yearly Own consumption rate	[%] of total generation
Hourly necessary energy supply	[kWh]	Yearly Unmet load	[kWh]
Fixed plant consumption	[kWh]	Expected loss of load frequency year 1	[hr/year]
Total installed power	[kW_p]	Expected loss of load frequency year 20	[hr/year]
Installed BESS capacity	[kWh]	Loss of load year 1	[kWh]
Inverter quantity	-	Loss of load year 20	[kWh]
Yearly generation degradation factor	[%/year]	Hourly battery energy level	[kWh]
Battery DoD	[%] of full capacity	-	-
Battery inverter quantity	-	-	-
Battery yearly degradation	[% / year] of full capacity	-	-
System lifetime	Years	-	-
Grid length	[km]	-	-
Grid losses	[%] of available hourly energy	-	-

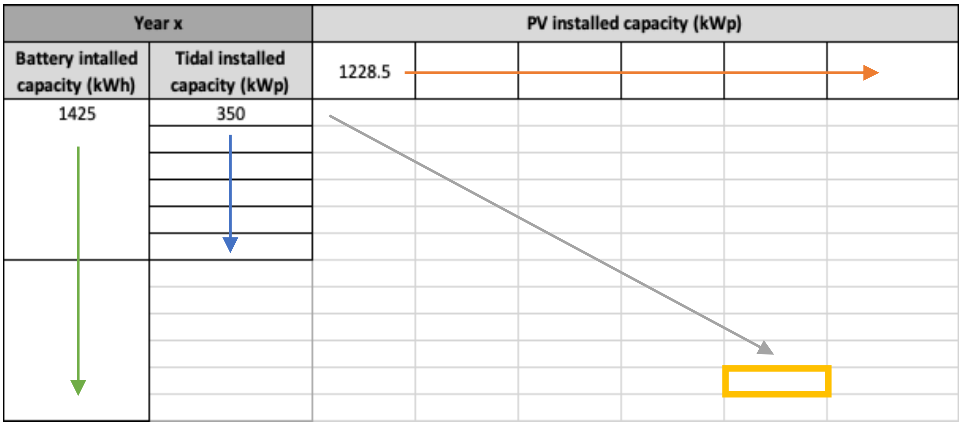


Figure 3.3 Configuration matrix for Excel based (exhaustive search) simulations showing increasing variable ranges and possible solution development through the matrix.

Figure 3.3 shows the matrix structure followed for the configurations and simulation order. The direction of variable increase for the installed battery capacity, peak installed PV capacity and the installed tidal stream turbine capacity are represented by the green, orange and blue lines respectively. The yellow box can be considered an optimal solution found for a specific performance indicator (PI) in this sector, also indicating a halt to the continued simulation of configurations and possible recalibration of the ranges or step sizes. The grey line represents a possible trend in increase or decrease of a PI of relevance, providing base for later simulation of selected configurations if required. A total of 120 simulations will be done upon which a trend for system response can be made for each individual variable increase or decrease. Based on this, more precise simulations could be done in order to avoid a further increase in simulation sample size and to find the configuration that satisfies the required operational conditions. Even so, it is very well possible that multiple combinations of the components satisfy the technical conditions, creating need for a secondary evaluation. This can be done by extracting the required results from the excel model and applying an external calculation for other PI's such as the OC rate, specific yield, battery level development, LOLH an LOL. Since this simulation does not automatically include any other cost or scenario consideration made by WEG in previous project assessments, an additional calculation section was added aimed at providing the necessary values required for specifically this study. As a baseline the conventional system performance was simulated using the original inhouse Excel model. This functions not only as a baseline for the functionality of the WEG model but also to provide the required indicator values to later compare the fully renewable system with the conventional hybrid.

3.2.3 Homer-pro model

HOMER-pro, as mentioned in section 2.2.3 is an outhouse software considered one of the best and most used GA based (hybrid) energy system optimization software currently available. The input parameters and variables necessary for simulation are given in Table 3.4.

The software will be used in the following stepwise approach:

1. Constructing a component-based system representing the FRES PV-TS-BESS hybrid system.
2. Input the required hourly generation profiles of the tidal stream turbine as calculated in the tidal stream turbine excel model.
3. Import weather, irradiation, temperature and location data provided by HOMER-pro databases.
4. Input controller type (load following, cycle charging, dispatch order). This imitates the consideration made in the Excel model to use the least cost component first before increasing capacity of others.
5. Input project economics such as the discount factor, inflation rate, system lifetime, (fixed) CAPEX and (fixed) OPEX.
6. Input optimization constraints (max annual capacity shortage, operating reserve).
7. Input any sensitivity cases for each of the input parameters.
8. Simulate the multi-year system performance and assess KPI's for optimization.

Table 3.4 HOMER-pro input values for project specification

HOMER-pro input parameters			
Generation	**Load**	**Economic**	**Optimization**
Hourly tidal generation data	Hourly energy demand profile	Discount rate	Project lifetime (multi-year)
Tidal turbine power curve values	Day-to-day random variability	Inflation rate	Minimum renewable fraction
Turbine quantity limit	Time-step random variability	Fixed capital cost (system)	Maximum annual capacity shortage
Irradiation data	-	Fixed O&M cost (system)	Operating reserve
Weather data	-	Component CAPEX	Optimization timesteps
Ambient temperature data	-	Component OPEX	Battery autonomy limit
Installed capacity limit	-	-	Renewable penetration limit
BESS type and operating values	-	-	Sensitivity cases for each variable
BESS capacity limit	-	-	Controller type (optimization strategy)

The SIT-250 (tidal turbine) and Load data are input into the system form external sources (own calculations). The specifications and required operational data for the converter, TRI-PV module and TESLA battery components are part of the HOMER-pro database. The software optimizes for the NPC of a system but provides also other indicators like the LCOE and Capacity shortage (LOL) if specified in the project file.

After all necessary values have been input into the GUI, Homer-pro evaluates the number of simulations to be made and does simultaneous sensitivity case simulations based on its selective and eliminating algorithm, by excluding configuration and scenarios that do not meet the economic or project constraints from the simulation list. HOMER-pro's GA based advanced vector engine requires only a fraction of the time for the multi-year, multi sensitivity case optimization simulations then would be necessary with the WEG model's exhaustive search method. This proves the necessity and advantage of using such a software built for energy system optimization and analysis. However, since limited insight is possible in the actual programming and algorithm used in HOMER-pro, a limitation remains in the user's freedom to investigate system behaviour based on specific variations of their choice since the objective of a simulation might not always be the cost optimization as is with HOMER-pro.

3.3 System losses and modelling assumptions

From the source of generation there are various system wide losses that need to be considered to more accurately estimate the capacity and performance. These losses occur between generation and load points and in different components of the system, like cable losses, inverter losses, losses in BESS and efficiency losses. Most losses are included in the component's individual generation calculations and data sources (PV Sol, HOMER-pro) yet can be defined in different ways. Some clarification is given here.

3.3.1 Inverter losses

As discussed, a crucial component in any renewable energy system is the inverter. Especially when working with different DC or AC generation components or loads. The choice for inverter influences the losses accompanied with the power transformation and efficiencies of energy storage and availability. As mentioned, the WEG Excel model uses the grid ready PV power as calculated by PV Sol which already includes any (string) inverter losses. The Tidal stream turbine model discussed in section 3.2.1 also uses the power values of grid-ready electrical power after (generic) inverter losses as given in [57]. The turbine model assumes no mutual losses due to turbulence effects of the turbines or changes in localized (bathymetry) conditions. Overall no additional inverter losses are included in the WEG model itself for the generation components. Even so the inverter can have a significant influence on the power output depending on its operational range and rated power. A mismatch of inverter choice can thus lead to lower performance of the integrated components. Appendix E provides the specifications of the inverter used within the PV Sol calculations, although this is of no further relevance for the simulations done in this study. In the HOMER-pro model a generic converter is used simulating any required size in relation to the installed capacity of the generation components with an AC to DC inverter and DC to AC rectifier efficiency of 95%.

3.3.2 Cable losses

HOMER-pro automatically includes these losses in the generation calculation of the PV component and by implementing a required operating reserve at each timestep as percentage of generation or load capacity [23]. HOMER-pro applies a PV derating factor of 0.85. This is applied to the PV array power output to provide a realistic power output compared to rated conditions. It accounts for factors like panel soiling, cable losses, shading, snow cover, aging etc. The effects of temperature on the PV array power output are included separately leading to the following formula for PV power as used in the HOMER-pro software.

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}}\right)[1 + \alpha_p(T_c - T_{c,STC})] \tag{3.11}$$

With Y_{PV} the rated capacity of the PV array at standard test conditions (STC), f_{PV} the PV derating factor, G_T the solar irradiation incident on the PV array, $G_{T,STC}$ the incident STC irradiation, α_p the temperature coefficient of power and T_c and $T_{c,STC}$ the PV cell temperature and PV cell STC temperature respectively. HOMER-Pro uses its own irradiation, weather and ambient temperature data sets (from NASA weather data) [23] for its calculations. For the tidal yield calculations in HOMER-pro the same input is used as for the WEG model, which is constructed in the Tidal stream turbine model based on current velocity data and turbine specifications for the multi-year lifespan of the project.

Within the WEG model the cable losses are set at 1% of the required energy per timestep [5] and are added to the load providing a value for the total required energy including AC (grid) and system cable losses. When looking at the following equations for cable resistance (3.12) and resistive losses (3.13):

$$R_{cable} = \rho * \frac{l}{A} \tag{3.12}$$

With R_{cable} the cable resistance, ρ the conduction material specific resistivity, l the cable length and A the cable cross sectional area and:

$$P_{loss} = R_{cable} * I^2 \tag{3.13}$$

With P_{loss} the resistive power loss in Watts and I the current through the cable it can be seen that this resistance increases with increasing cable length and decreases with cross sectional area increase. Since the cable losses thus depend on the length and thickness of the cables it is advisable to place the generation components or entire energy system close to the load points and use the appropriate cable thickness as to reduce the losses during transfer. However, thicker cables would also increase cost, indicating that an optimality in this can to be found. This optimality consideration of cable losses of the PV array, tidal modules and other components is not considered in the simulations. An estimated grid length of approximately 13.8 km and the accompanying AC grid cable losses (8% in WEG model) are added to the load or required energy as previously mentioned.

3.3.3 BESS capacity losses

For the BESS component the roundtrip efficiency of 87% is used as specified in Table 2.14 and the specification of the TESLA Powerpack (Appendix D) that will be used in both the WEG and HOMER-pro model, with a maximum DoD of 90% and available capacity of 90% of the rated capacity. The roundtrip efficiency is a combined efficiency of the voltaic and coulombic efficiencies as can be seen from equation (3.14).

$$\eta_{battery} = \frac{E_{in}}{E_{out}} = \frac{Q_{discharge}}{Q_{charge}} * \frac{V_{discharge}}{V_{charge}} \tag{3.14}$$

With Q and V denoting the respective discharge and charge capacities and voltage. For the BESS a yearly capacity decrease (degradation factor) of 2% is used in the WEG model with a warranty lifetime of 10 years so determining its replacement when Battery health or capacity drops under 80% of the original state or after a maximum cycle life achieved with 350 cycles/yr. In HOMER-pro the BESS is limited by the pre-set expected lifetime of 10 year or an annual throughput (kWh/yr) meaning its replacement is determined by a time factor or a total energy throughput during operation.

3.4 Simulation assumptions

For the simulation of this fully renewable hybrid energy system some additional assumptions regarding the operational conditions and (input) variables are made:

- The installed capacity of each generation component and the storage component are considered variables.
- The Load profile is considered to be constant every day without, hourly, daily or seasonal fluctuations. Monthly energy demand varies only due to a difference in day count.
- The sizing range of the components is influenced by the cost per installed capacity, meaning it is preferred to increase first the size of the cheapest component, and not necessarily that of the component with highest specific yield. Within HOMER-pro all possible configurations are assessed making this consideration unnecessary.
- The yearly degradation of solar PV and tidal stream turbine is considered equal at 0.5 [%/year]
- No land area or sea area limitations are taken into account and no legislative requirements are of effect on the feasibility assessment during simulations.
- In the simulations it is assumed the entire generation and storage capacity is installed in year 0 and the performance is assessed based on the year 20 statistics since this is the end of the project lifetime and dictates the necessary system requirements in previous years. Realistically a modular installation of generation capacity and perhaps storage capacity is preferred to increase component lifetime and reduce overgeneration in early years of operation.
- The LCOE calculation is based on cost of installation and operation only with a fixed cost for the accompanying powerhouse and grid necessary for the energy system.
- A real discount rate of 7 [%] and inflation rate of 1.5 [%] will be used as given by WEG.
- BESS price decrease is considered to be similar to the inflation rate.
- The capital and operational cost of the BESS and solar PV components are based on the values used in the WEG model for the conventional hybrid system calculations.

4

Case study "Panlaitan"

The context of feasibility assessment, the principles of optimization and generation and the assessment framework of chapters 2 and 3 are here applied to a case study for the island of "Panlaitan". Location and climate characteristics are described in section 4.1 to provide context for this project. Subsequently the process of load assessment and profiling is given in section 4.2 followed by a description of the expedition activities aimed at acquiring more data on the tidal system and its potential in section 4.3, including the construction of the current velocity datasets used in further calculations. Section 4.4 will include the simulation input values for this case to be used on the models decribed in the previous chapter.

4.1 Location and climate

The targeted island for this case study, "Panlaitan" shown on Figure 4.1, lies within the Palawan island region as shown in section 1.2, and is currently using small diesel generators for limited and cost intensive energy supply of the encircled inhabited area. A site assessment was made for this island using global maps [5], and a site visit by employees of WEG.

The Philippines land area is spread out over a region in the Southeast Asian equatorial belt. Meaning there can be different weather conditions in different areas characterized by high average temperature, humidity and quantities of rainfall [18]. These are factors that need to be identified, as they might influence design considerations in later stages of energy system implementation. For this feasibility study however factors such as temperature can influence the solar PV performance and susceptibility to extreme weather conditions can create a preference for certain technologies (floating tidal stream turbines). Lower irradiation might lead to resizing of solar PV, or high winds might cause unwanted currents and operating conditions in the ocean. Based on (among other) rainfall distribution, four climate types can be recognized in the Philippines as shown in Table 4.1.

Table 4.1 4 (sub)-tropical climate types distinguished in the Philippine island regions

Climate type	Description
1	Dry season November till April and wet season during the rest of the year
2	No dry season with majority of rainfall between November and January.
3	No clear distinction between seasons, relatively dry between November to April, wet during rest of the year.
4	Evenly distributed rainfall throughout the year

Differences in climate result in different types of tropical sunshine (intensity, cloud coverage etc.), temperature and rainfall. Only two seasons can generally be distinguished, wet and dry, determined by the amount of rainfall. The warmest months are from March to October with highs in March and April, contrasted with relatively cooler air brought in by the winter monsoon in November till February. Monsoons are caused by large sea breezes originating from temperature differences (warmer or cooler) between land and sea. The summer monsoon accompanied with heavy rains brings between 1000-5000 millimetres of rainfall depending on the terrain. These monsoon rains are often not accompanied by high winds or waves, which is beneficial when looking at their possible impact on tidal turbines and (elevated) PV systems. The rainfall however is useful for clearing soling and dust off the PV modules. In Table 4.2 an indication of the periods of higher/lower rainfall and temperature differences is given.

Figure 4.1 The island of Panlaitan, encircled the location of residential and municipal load points, the measure indicating the island size and the range of possible channelling effects of currents. [56]

Table 4.2 Indication of seasonal characteristics throughout the year [57]

Months	November-February	March-May	June-August	September-October
Rainfall	Lower rainfall averages (dry season)		Higher rainfall averages	
Temperature	Cool	Hot		
Season	Cool dry	(Hot dry)	Rainy	

The Philippine region is located on the typhoon belt, submissive to storms during the months of July to October. The effects of these storms are more noticeable in the north-Eastern region of "Luzon", with a diminishing gradient towards the south-west. Statistics gathered form the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) show an average of 27 storms or typhoons per year entering the Philippines area of responsibility (PAR), with an average of 9 storms that make landfall across the Philippines [57]. PAGASA categorizes typhoons into five categories depending on windspeeds as shown in

Table 4.3. The temperature average over all the weather stations in the Philippines is 26.6 degrees Celsius, with cooler days occurring in January (average 25.5 degrees Celsius) and warmer days during May (mean of 28.3 degrees Celsius). Depending on elevation these temperatures can differ. Generally, year-round high humidity is expected, due to the extraordinary evaporation of seawater surrounding the islands, the monsoon winds, and the abundant rainfall typical for tropical regions [57]. This ambient temperature falls within the operating range of components like the BESS and indicates a necessity for appliances like fans and refrigerators for cooling. Furthermore, no excessive maintenance for soiling of PV modules is required and seeing the location of the island of Panlaitan, moderate risks are assumed for damages to components due to extreme weather conditions.

Table 4.3 Tropical cyclone intensity scale [18]

Severity of storm	Windspeed in km/h
Super typhoon	>220
Typhoon	118-220
Severe tropical storm	89-117
Tropical storm	62-88
Tropical depression	<61

Table 4.4 Island geographical specifications [58]

Geographical property	Panlaitan
Highest elevation [m]	81.7
Latitude	12.120360
longitude	119.846480
Surrounding water depth range [m]	1.8-29

The latitude and longitude coordinates, as well as the maximum elevation and water depth ranges (

Table 4.4) can be used for more precise RES potential data collection in both PV Sol and the HOMER-pro model and for the construction of the tidal data set. Since the potential of tidal stream energy is studied here, a preliminary survey of the surrounding waters was made by using marine (navigational) maps indicating water depth, measurement buoy positions, tidal amplitude and seabed contour lines as can be seen on Figure 4.6. The Navionics application indicates approximate changes of tides during the day, high and low tide times and location of tidal measurement equipment [59]. It is originally used by ship captains to plan routes but is here useful to give an estimation of the conditions at the targeted locations since limited data is available for this remote area.

4.2 Load assessment and profiling

Panlaitan has several small generators (<50kW) that are used for short-term electricity generation and has limited (improvised) electrical grid connections in place. Since no historical energy demand data is available, and no measurement equipment can be placed on a working grid (or at all due to lack of a grid) different approaches were used to make the actual demand estimations.

Based on a study of rural energy use in Malaysia [7], a first estimation could be made for the appliance type, usage and energy demand for the island of Panlaitan. This resulted in an average daily energy use per household of 12.56 [kWh/day]. Multiplying this by the indicated number of households gives an estimate for the total average daily energy use for the entire island of Panlaitan of 9.34 [MWh]. This however does not include municipal appliances, street lighting, or any other non-residential energy consumption, which should be taken into account. Also, it gives an estimated value higher than the average 4-person household energy use in developed countries like The Netherlands (12.3 kWh/day) [60]. Using the annual energy consumption per capita in the Philippines (741 kWh) [61], as measured mostly in the urban areas can also mislead in the actual energy demand for rural areas. These estimations also do not provide an hourly load distribution which is needed for accurate simulation. More precise and detailed load profiles and overviews of energy use characteristics are required which leads to increased accuracy of energy system sizing. As such, load estimates for Panlaitan are made using information gathered from [42]:

- Interviews with residents about appliance types they own or will buy once 24-hour energy supply is available including current status of electrification of their household.
- Day and night-time expected electricity use.

- Cost expectations for electricity
- Any data on fuel consumption (if generators are installed).
- Typical load curves for public utilities such as municipal offices, clinics, school, water churches etc.
- Change of consumption patterns based on experience data of electrified rural areas.
- Size of consumer groups and demographic data.

For each type of load point consumption patterns were made using the available utilities, appliance listing and any records of usage. This should be done for every community (island) separately since there can be differences in consumption patterns and load points. experience data and available images and sitemaps are used to classify the different load points and their location.

Firstly, for an initial scale assessment and estimation of daily energy use was made based on the number and power consumption of typical appliances. The following formula was used for this [7]:

$$\frac{Wattage * hours\ used\ per\ day}{1000} = daily\ KWh\ consumption \qquad (4.1)$$

A map of the different households, municipal facilities, schools, churches, sports fields and other load points was made. This sitemap can be seen in Appendix F. A distribution and duration of energy use throughout the day was used to differentiate between classifications of load points as can be seen in

Table 4.5. Here the estimated energy use for all combined residence type 2 and all stores is given. The individual load profiles of these load types (residence type 2, stores, schools) can be seen on Figure 4.2. The energy demand value is then multiplied by the amount of load points per type and summed for an overall energy demand of the whole island for a full day as seen in Table 4.6.

Table 4.5 Typical appliance use and energy consumption for Residential type 2 and commercial facilities [4]

	Residential type 2				**Store**			
Appliance	**Wattage**	**Quantity**	**Hours used**	**kWh/day**	**Wattage**	**Quantity**	**Hours used**	**kWh/day**
Light bulb	10	10	9.5	0.95	10	12	8.0	0.96
TV	100	1	8.8	0.88	100	1	12.5	1.25
Electric Fan	30	3	16.8	1.51	50	8	10.0	4.00
Refrigerator	150	0	0.0	-	300	3	12.7	11.43
DVD player	50	1	1.0	0.05	50	0	0.0	-
Hot Iron	1000	1	1.4	1.40	1000	0	0.0	-
Water Pump	1200	0	0.0	-	1200	1	1.0	1.20
Washing Machine	1000	0	0.0	-	500	0	0.0	-
ACU	300	1	2.5	0.75	800	0	0.0	-
Computer	40	1	8.8	0.35	300	4	0.8	0.96
	Total kW	**1.68**		**5.88**	**Total kW**	**3.92**		**19.80**

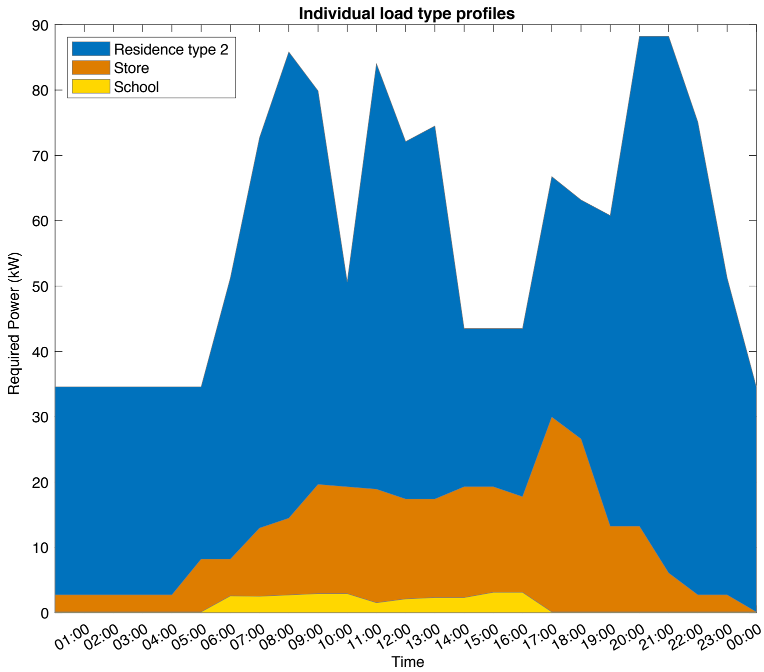


Figure 4.2 Load profile for residential type 2, store and school load points on Panlaitan indicating the cumulative energy demand per load type and the load distribution throughout a day.

Table 4.6 Complete load estimation for Panlaitan (year 1) [4]

Type of load points	Number of load points	kWh/day	Total daily energy use per class (kWh)	Total yearly energy use per class (kWh)
Residential type 1	353	3.43	1208.3	441044
Residential type 2	239	5.88	1402.4	511872
Residential type 3	31	6.6	199.8	72928
School	2	14.9	29.7	10855
Church	6	3.5	20.9	7621
Store	16	19.8	301	109850
Barangay hall	1	8.2	8.2	2988
Basketball court	4	1.2	4.8	1752
Total	**652**	**-**	**-**	**3281.84**

Looking at the distribution of the energy demand of all load points combined, it can be seen on Figure 4.3 that the residential sector is by far the most requiring with 88% of the total energy demand and municipal and commercial facilities only accounting for 12%. These load profiles are subsequently used to make a combined daily load profile as seen in Figure 4.4 and provide a quantity for the yearly energy demand. Normally hourly, daily and seasonal fluctuation in energy demand have to be incorporated in the energy demand profile, however, for Panlaitan, no historical data is available and negligible changes are assumed. As such, no fluctuations have been implemented in the load curve. Still a comprehensive estimation is used for the load. The load type assessment table for the load profiling of the load types can be found in Appendix G.

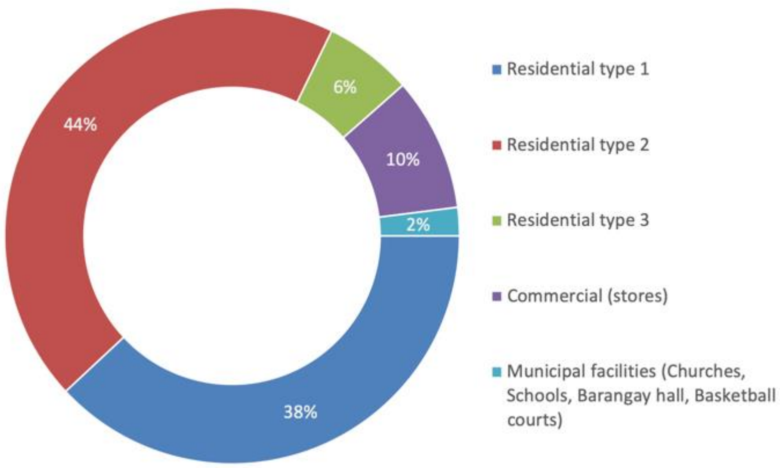


Figure 4.3 Energy demand distribution of Panlaitan per load category [4]

The estimate following from this more detailed analysis is 3175.09 [kWh] per day with a peak load demand of 196.78 [kW]. After addition of the expected losses and powerhouse own consumption of the energy system the required energy demand is 3525.31 [kWh] per day with a peak load of 216.38 [kW] in year 1 and 6919 [kWh] with a peak load demand of 426.55 [kW] in year 20 as can be seen on Figure 4.4. The difference between the initial estimations and the second more detailed household classification approach done by WEG shows the importance of correct data acquisition by site-visits to avoid system oversizing. The values and profiles attained with the second more detailed approach will be used in the simulations for system optimization.

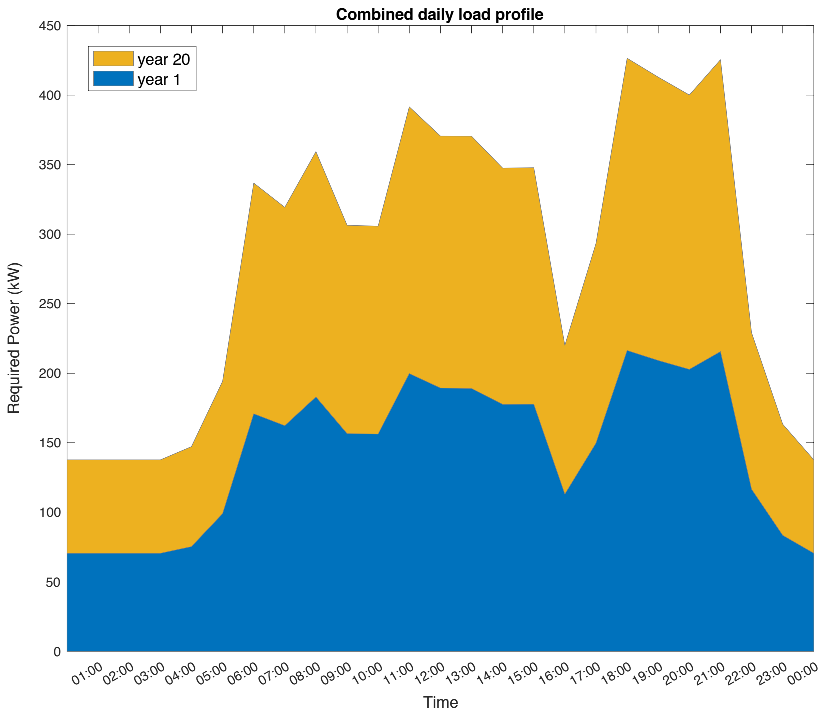


Figure 4.4 Combined daily load profile in year 1 and year 20 for Panlaitan

4.2.1 Peak power and energy requirement evolution

In order to simulate the reliability of energy supply over the system lifetime (20 years), the expected demand growth is included. A projection of the demand growth and a monthly energy demand distribution can be seen on Figure 4.5. These were constructed using the experience data from WEG and the values mentioned for initial (unleashed suppressed demand) growth in the first 5 years (5-6%) and sequential growth percentage (3%) for the remaining years (5-20). The monthly fluctuations observed here are related to the number of days in each month. A difference in peak power of approximately 216 KW and 427 kW, and annual energy demand of 1.18 GWh and 2.25 GWh in year 1 and 20 respectively is found. These values are used in the initial system design and performance assessment of the system in year 20.

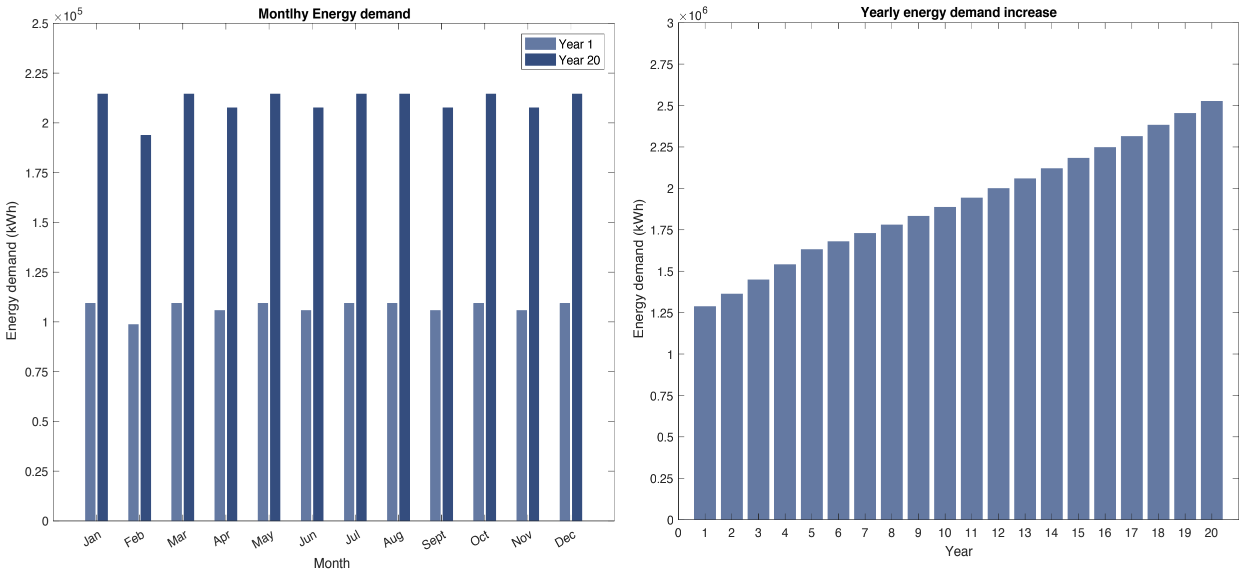


Figure 4.5 Monthly energy demand in year 1 and year 20 (left), energy demand growth over system lifetime (right),

As can be seen in Table 4.7 the difference between the year 1 and year 2 energy demand and peak load differ significantly. The annual energy demand increases with almost factor 2 and the peak load increases with 59 kW (27%). The peak load coverage from a renewable intermittent energy source is not as easily determined as the dependable power generation of a diesel generator. Only by simulating the expected power output and BESS capacity on an hourly basis can the performance of the fully renewable system be validated for these specific load values.

Table 4.7 Energy demand and peak load increase

Year	**Load (kWh)**	**Necessary energy incl. losses (kWh)**	**P_min (kW)**	**P_max (kW)**
0	0	0	0	0
1	1.158.724	1.286.739	71	216
5	1.475.246	1.630.784	89	229
10	1.710.214	1.832.040	103	244
15	1.982.607	2.182.263	119	259
20	2.298.385	2.525.500	138	275

4.3 Tidal data acquisition expedition

Since national tidal system and current velocity data is not easily accessible (or free) in The Philippines, and for the most incomplete (not covering rural areas), the tidal system classification and tidal potential for the island of “Panlaitan” required local measurement thru a planned expedition. As such trying to avoid excessive costs related with third party involvement for measurements, and to gather the required data for tidal stream energy yield calculations and potential assessment for turbine deployment. Multiple sources were used attempting to classifying the tidal conditions and prepare the measurements including the “Navionics” application for sea navigation [59], reports of global tidal conditions and affected areas, tide forecasting websites for the island of Coron (Palawan region) [29], and consultation with a local representative of “Tocardo” and “Sea and Land Technologies” (local Singaporean maritime equipment specialist). The measurements were performed for 2 islands (“Panlaitan”, “Bulalacao”) in the same region as to expand the effectiveness and the area of measurements for this expedition and validate any estimations or assumptions, however only the island of Panlaitan will be discussed in this section.

4.3.1 Water depth and bathymetry

For measurement site selection a local analysis was made of the water depth and bathymetry of the surrounding waters. The geography of the islands and reefs can indicate zones of possible narrowing or tunnelling effects that can increase or block currents. Sublevel currents can be pushed up or bounce off submerged blockades influencing the currents in the entire area in a complex and fairly unpredictable matter. Detailed analysis of the current flows would be required to understand the actual influential factors in the area (turbulence, updraft). Looking at the positioning of housing on islands can indicate the influences of weather conditions. Houses are built on the sheltered side and around waters with less fluctuating current or high waves. Harbours indicate less suitable areas for tidal turbine deployment. As can be seen on Figure 4.6. An analysis of the environment indicated suitable regions for measurements and excluded those that did not fit the requirements like installation depth for the selected tidal turbines or distance from load points.

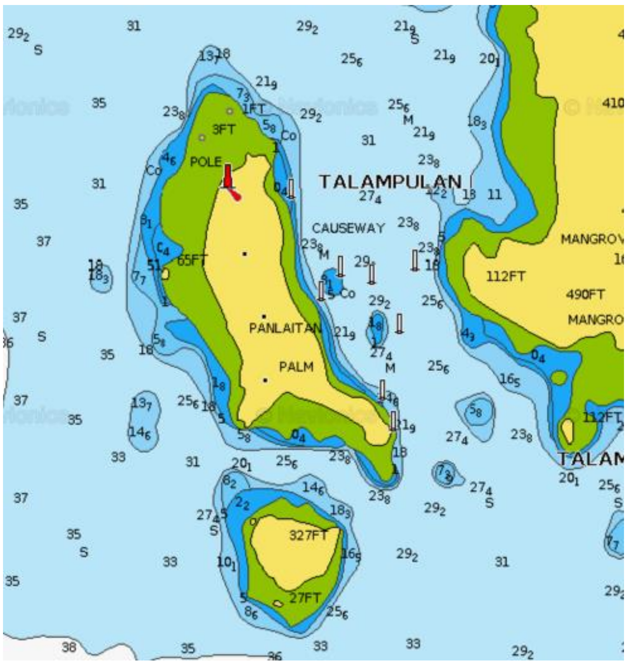


Figure 4.6 Map of Panlaitan showing sea level depth and topography [59]

4.3.2 Fishing activity and coral reefs

Fishing activity like nets/ pearl farms/ fishing boats/ floating fishing structures indicate slower steady currents (steady nutrient flow for marine life). It also makes deployment of tidal stream turbines more difficult yet indicate areas that are less susceptible to extreme weather conditions, which would be beneficial for turbine deployment.

Figure 4.7 Fishing nets (left) and coral reefs (right) around the island of Panlaitan (and Coron).

The coral reefs and obstructions under water were not always visible on (free) satellite images. Either detailed satellite images or local site assessment are needed for this. On site it could be seen relatively quickly where the reefs are due to indicators by the local communities (bamboo sticks/floaters/buoys). In general, within distance of 50 to 100 meters from the shoreline the reefs and sand beds are still quite shallow, influences from the seabed and islands is still quite large and deployment is thus not effective. To crosscheck the predetermined measurement locations and expected tidal behaviour the local expertise of the water, its current, reefs, and weather effects is crucial. For this reason, a local diver and local residents/fishermen were asked to join some measurement activities to better navigate and determine the most suitable locations and find the strong steady current sites.

4.3.3 Tidal current velocity measurements

Due to the unknown potential around these island (which cannot be deducted from general data in this case) the objective from WEG here was to first assess the potential and necessity of performing any long-term measurements since there are high costs connected to the measurement equipment and placement by any third party. After consultation with “Sea and Land Technologies” And “Nortek” (sensor equipment manufacturer) a sensor and measurement approach was selected suitable for the type of spot measurements and short-term measurements to be performed and in line with the description of measurements in section 2.3.5.

In this rural area no GPS guided vessels were available within the expedition budget or timeframe and attaching the sensor to a single location on the seabed would limit the amount of measurement locations that could be visited. Since one of the targets was to assess what kind of current behaviour could be found around this island there was need for flexibility and easy deployment, for which the “Nortek Aquadopp” sensor was selected (Appendix H). The sensor and mounting frame is lowered into the water with a Kevlar reinforced cable, as can be seen on Figure 4.8, and connected to an onboard data box and display for real time monitoring. The sensor was selected due to its flexibility in deployment and self-stabilizing properties, making it easy to use within the required range of accuracy for potential spot measurements.

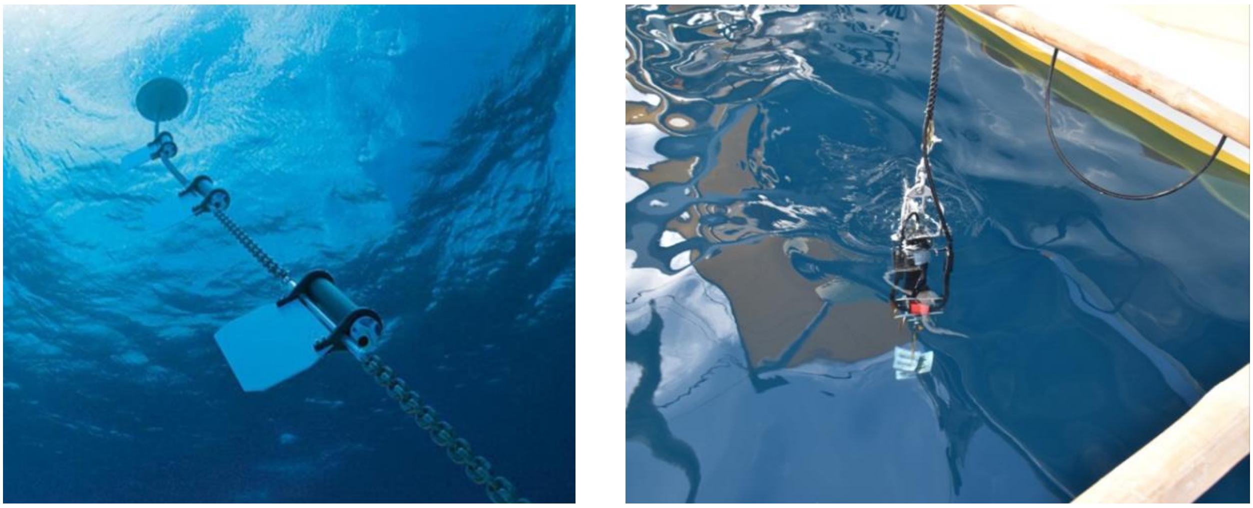


Figure 4.8 Nortek Aquadopp sensor deployment continuous profiling (left), spot measurements performed around Panlaitan with sensor placed in mounting frame attached to Kevlar reinforced data cable (right).

In order to decide the best timeframe for a site visit the tidal behaviour was studied. There are in general 3 types of systems as discussed in section 2.3.2. By analysing the tidal forecasting information [29] available from a buoy in a nearby harbour of the island of "Coron" and the local type of tidal system being "mixed semi-diurnal " a 1 week window was selected from the 23rd till the 29th of May. This window was selected being between Spring and Neap tide, avoiding any measurements that might create a biased result of best (Spring) or worst (Neap) tidal conditions as such providing an average tidal behaviour time frame. Additionally, the timeframes within a 24-hour period were selected avoiding slack water conditions around high and low tides.

Due to tidal turbine minimal deployment depths and the sea level depths as indicated on Figure 4.6 measurement depths of 5, 10 and 15 meters were used with occasional measurements at 20 and 25 meters (for reference). A 3-minute continuous measurements at each depth allowed for filtering and averaging of the current velocity and construction of a basic current velocity profile. In general, a higher amplitude and consistent tide changes results in higher mass flows and thus stronger currents. If no (accurate) data is available as in the case of Panlaitan both local information and measurement/indication points can be used to estimate amplitude and tidal behaviour. For Panlaitan an average spring tide amplitude of +/- 1 m was confirmed by indicators along the coast, like pier poles, flood barriers, house placement heights.

4.3.4 Data collection and processing

During measurements the values were logged by the on-board data logger and later processed for removal of faulty measurements and averaging of current velocities. Every measurement location was logged with a GPS device for later reference. The collected data can be found in Appendix I. A representation of a current velocity profile is given in Figure 4.9 of a single location and the entire measurement area is shown in Figure 4.10. The measurement locations differ slightly from the aimed systematically selected (grid wise) sites determined before the expedition due to local findings like fishing activity, slack water or rough conditions causing ineffective measurement conditions. At each location the boat (Banka) was anchored and directed in line with the current for increased stability. The sensor was then systematically lowered and secured at the required depths.

The collected data shows little potential with currents between 0.1 and 0.6 [m/s] at various depths and not in range of any turbine operational velocities. The data collected from this site visit to Panlaitan shows that the expectations for tidal stream potential were too optimistic. The tidal system does show a mixed semi-diurnal behaviour as predicted. A preliminary conclusion can be draw that for this area the potential is thus insufficient, and further efforts to perform full cycle measurements or expect effective deployment of tidal stream turbines could be halted. These measurements did however provide enough insight to create a data set with similar tidal system behaviour yet varying strengths to investigate further the technical performance of tidal stream turbine implementation in similar locations or tidal systems. To create these hourly current velocity datasets a model is used that allows for adaptation of the tide constituents described in section 2.3.2.

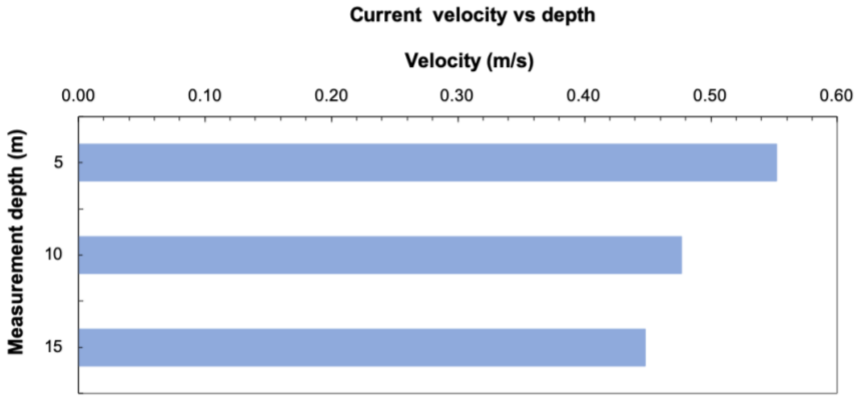


Figure 4.9 Velocity measurement example of current velocity at each measurement depth performed around Panlaitan

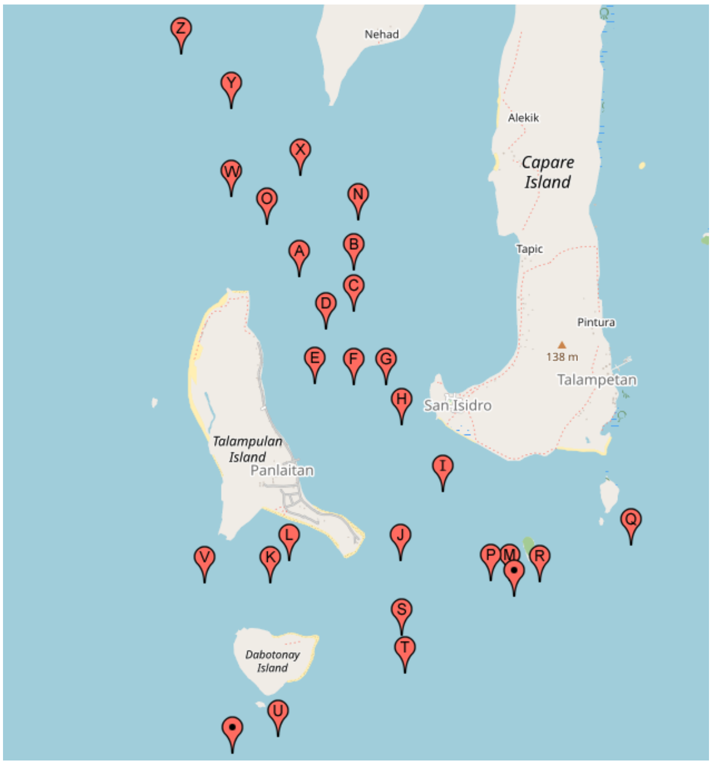


Figure 4.10 GPS marked measurement sites around Panlaitan

4.3.5 Simple tidal energy model (STEM)

To create an hourly current velocity data set approximating the condition as found around the island of Panlaitan a Simple Tidal Economic Model (STEM) was used which was developed by Jack Hardisty (2007) [27] and is based on the theory described in section 2.3.2. The STEM is designed to simulate tidal currents for hourly timesteps over 12 months, providing differentiation between Neap and Spring tides, equinoctial tides, shallow water and diurnal cycles and possible overlap. The economic side of the model was not used in this study however the harmonic decomposition used to create the current velocity data for different locations and tidal systems was used to construct the input data for the tidal stream turbine energy model as discussed in section 3.2.1. From the measurements performed in the previous section the tide system classification (mixed semi-diurnal) and current velocities or tidal amplitudes were used to first create a velocity set approximating the conditions of Panlaitan as close as possible. Subsequently the same type of system was used to create two more datasets with current velocities within the operational range (1-4 m/s) of the considered tidal stream turbines of section 2.4.2.1. With these current velocity data sets more precise energy yield calculations were made to first of all conclude on the low energy potential around Panlaitan and secondly provide the necessary input for energy system simulation. The STEM is constructed out of 5 stages [27] being:

1. Identification of tidal data sites representative for tidal flow analysis
2. Acquiring tidal condition parameters (spring, neap, flood, ebb surface current)
3. Harmonic decomposition to determine the current amplitudes for the six harmonic factors
4. Synthesizing the 12-month time series of hourly current velocity data
5. Calculating the potential hydraulic/electrical power.

Stages 1 and 2 have been discussed in the previous sections. For the case of Panlaitan the harmonic values in the STEM and the resulting current velocity range, energy yield and highest achieved capacity factor (of all three turbines) are given in Table 4.8. It follows that the “Schottel” SIT-250 turbine performed best under these tidal conditions, and this turbine was selected for this energy system assessment.

Table 4.8 Current velocity data set harmonic elements and energy potential values

Tidal scenario	MU2	SU2	MU4	KU2	KU1= OU1	Formzahl number	Max flow [m/s]	Mean flow [m/s]	Cf (SIT-250)	Energy yield (SIT-250) (kWh/year)
1	0.40	0.29	0.15	0.02	0.41	0.85	1.47	0.44	0.014	8843.5
2	1.76	0.79	0.15	0.06	1.08	0.85	3.66	1.16	0.24	145690.42
3	2.22	1.25	0.15	0.08	1.47	0.85	4.98	1.57	0.32	193789.71

As can be seen on Figure 4.11 the 3 different datasets differ in amplitude of current velocity yet maintain their neap-spring cycle diurnal inequality and shallow water shapes. Due to the amplitude differences the semi-diurnal inequality effects are less prominent in the second and third scenarios. All sets however show changing amplitudes of the current velocities in ebb flow than in flood flow timing over the spring neap (month) cycle, varying mainly in the available potential (hydraulic) power. Following from the energy yield and capacity factor tidal scenario 3 is used in all further calculations and simulations of the FRES in Excel and Homer-pro.

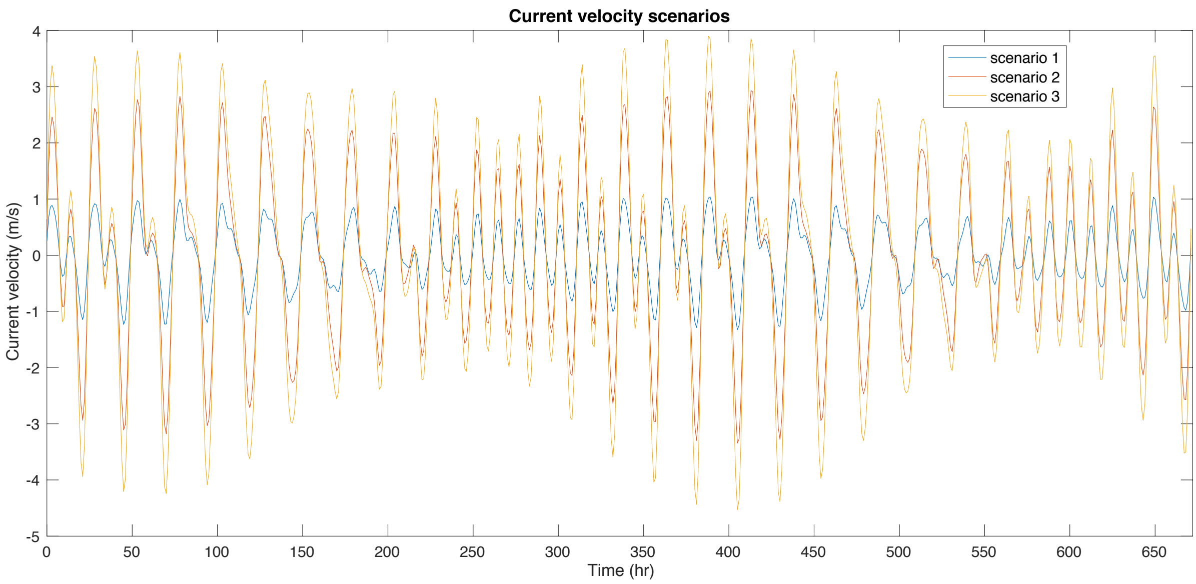


Figure 4.11 Current velocity profiles of 1 lunar cycle (28 days) for the 3 STEM current velocity scenarios: 1 actual scenario around Panlaitan; 2 adapted scenario for higher average current; 3 adapted for higher current amplitude differences.

The acquired current velocity data, together with the solar PV and load characteristics and specifications discussed in section 2.4, can subsequently be used for the FRES simulation and optimization. The simulations and optimization using the WEG Excel based model and HOMER-pro were performed as discussed in chapter 3.

4.4 Simulation values for Panlaitan

Table 4.9 shortly summarizes some of the important technical input values and constraints as defined in Excel and HOMER-pro, with which the simulations for full system lifetime performance of the solar PV – Tidal stream – BESS energy system will be performed.

Table 4.9 Constraints and input values for FRES system simulation and optimization in Excel and HOMER-pro.

	Excel (ES - model)	**unit**	**HOMER-pro**	**unit**
Solar PV generation	PV Sol dataset	Hourly values	HOMER dataset + module specifications	Hourly values
Solar PV capacity step size	94.5 (per 350 modules)	[kW] per string inverter	94.5 (per 350 modules)	[kW] per string inverter
Tidal stream generation	Tidal turbine model dataset	Hourly values	Tidal turbine model dataset	Hourly values
Tidal stream capacity step size	350	[kW]	70	[kW]
Yearly PV and TS degradation factor	0.5	[%]	0.5	[%]
BESS DoD of total capacity	80 (between 10-90)	[%]	80	[%]
BESS yearly capacity degradation	2	[%]	-	-
BESS end of lifetime capacity	< 80	[%]	< 80	[%]
BESS capacity step size	475	[kWh]	210	[kWh]
Load variability (daily)	0	-	0	-
Capacity shortage	1	[%]	1/ 0.1 / 0.01	[%]
Minimum renewable fraction	100	[%]	100	[%]
Real discount rate	7	[%]	7	[%]
Inflation rate	1.5	[%]	1.5	[%]
Diesel fuel price increase	5	[%]	5	[%]
Diesel fuel price	0.8	[$/L]	0.8	[$/L]

5

Simulation and Optimization results

The results of the simulations performed for the FRES and conventional energy system in both the WEG Excel based model and HOMER-pro will be discussed here. Section 5.1 and 5.2 will analyze the individual tidal stream turbine and solar PV power respectively. A combined generation and an intermittency analysis follow in section 5.3. Subsequently the key performance indicators as defined in section 3.1 will be discussed in sections 5.4 through 5.7, with any additional finding form the Excel based simulations in section 5.6. Finally, section 5.8 will cover any sensitivity analyses performed in HOMER-pro.

5.1 Tidal stream power generation

Following from the current velocity data set and the tidal turbine (Excel) model the rectified current velocity, hydraulic and electrical power output can be calculated. The daily energy yield of an entire year (Figure 5.1) shows the expected periodic repetitive structures due to the cyclical nature of the tides and increase/decrease on semi-annual and bi-monthly frequencies. The equinoctial highs around March and September are visible in the graph showing high daily energy yields with the latter being lower due to the declination differences cause by the earth tilt relative to the sun. In general, a fairly systematic yield structure can be distinguished for the entire year and repeats itself in any subsequent years. A degradation factor of 0.5 [%/yr] is used over the system lifetime, meaning the energy yield of a single turbine in year 20 (186055 kWh) compared to year 1 (193789 kWh) decreases with 3.8%.

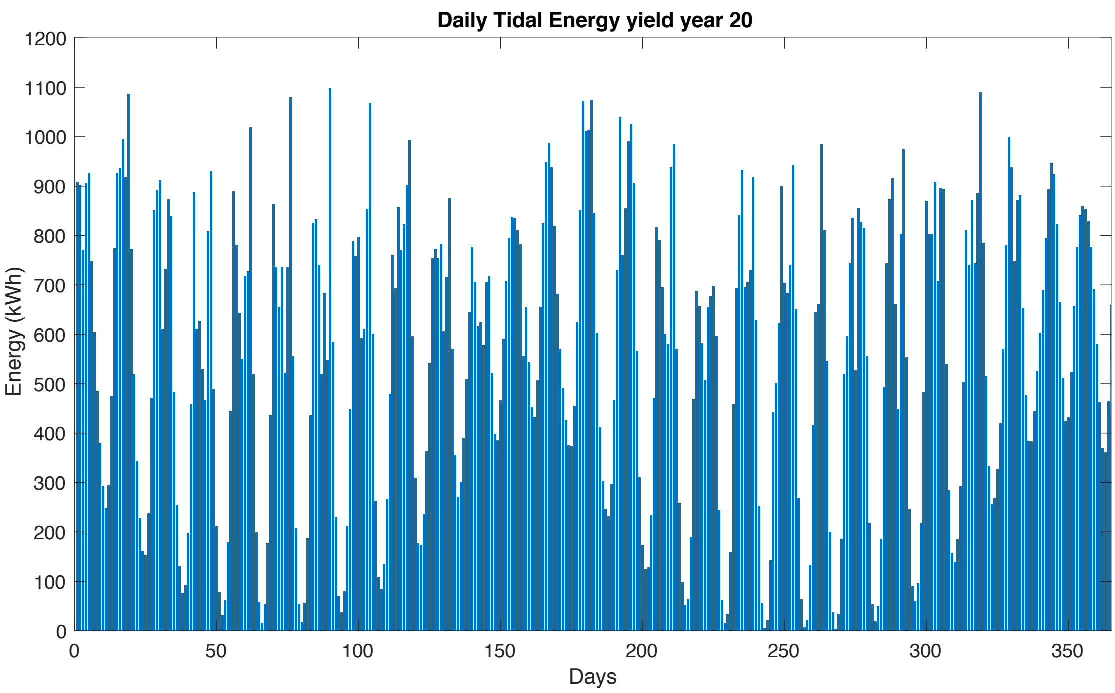


Figure 5.1 Daily tidal stream turbine energy yield in year 20 at 70 kW installed capacity.

In Figure 5.2 the current velocity, rectified current velocity, hydraulic potential power and the actual grid ready electrical power output of the “Schottel” SIT-250 turbine are given for the month of October. It is visible that with the reduced current velocity around neap tide a reduction in hydraulic power follows and similarly a reduction in the electrical power. This indicates the direct effect of tidal system elements on the electrical power output. Important is thus to analyse the energy system performance during these periods of lower tidal energy generation since any shortcomings in energy generation from the tidal stream turbines will most likely occur here.

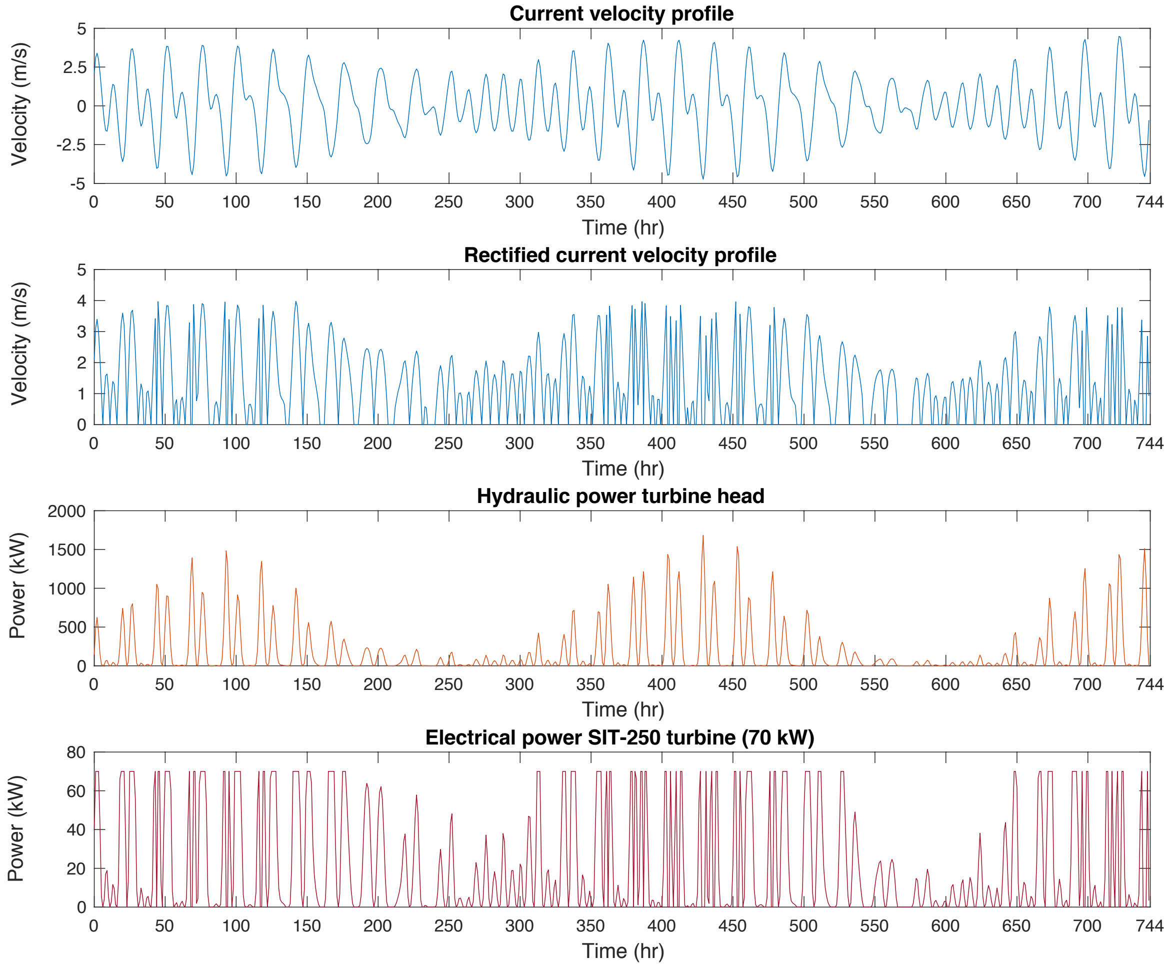


Figure 5.2 From top to bottom, the current velocity profile, rectified current velocity profile, hydraulic power and turbine electrical power for the month of October, indicating intermittency in current velocity and power output as well as the capped electrical power output due to turbine rated power value of a single SIT-250 turbine.

When zooming in on the tidal generation on specific days throughout the year however, it is clear from Figure 5.3 that the differences in generation can be significant. A best day (highest daily yield) and worst day (lowest daily yield) scenario are compared. This large fluctuation in generation potential causes the operational range of the energy system to fluctuate as well and creates a necessity for large size generation capacity or storage to provide sufficient energy during times of low production, with the consequential overproduction or adequate production on best days. An average tidal production curve is difficult to make due to the changing nature of the day to day current velocity and tidal behaviour. However, the effect of this will be analysed further in section 5.3.

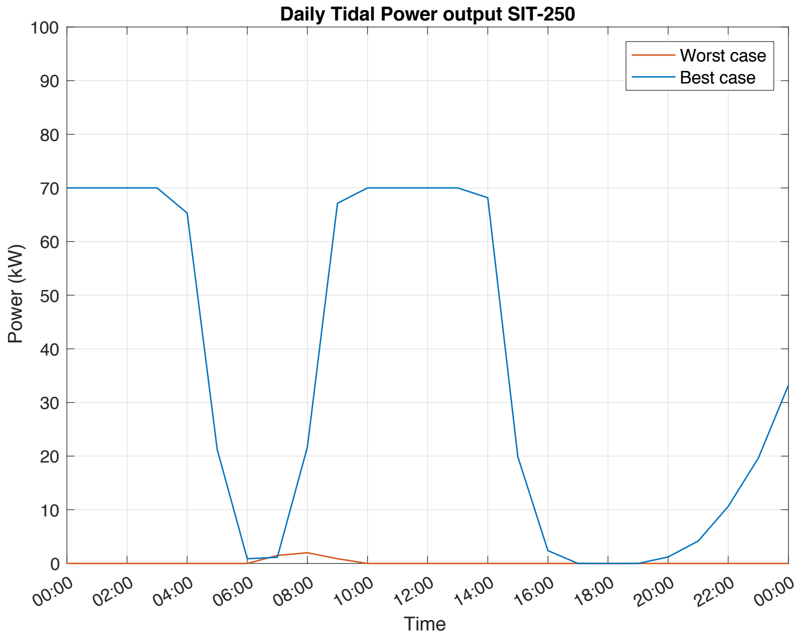


Figure 5.3 Best and worst day tidal power output for a single SIT-250 tidal stream turbine, taken from 2 different days of a single lunar cycle.

5.2 Solar PV generation Panlaitan

The PV generation components and power values, discussed in section 2.4.3, are used as calculated for Panlaitan in PV Sol and as provided by WEG. However, the installed capacity can be varied within the simulations by multiplying the power output by a factor of installed capacity increase. It is here assumed every additional solar PV installed capacity operates identically. The daily energy yield plotted over the year (Figure 5.4) shows fairly irregular generation with a higher yield between March and May, which are considered the warmer or sunnier months, with the highest daily energy yield of 3846.9 [kWh] and a low of 478.1 [kWh]. It is assumed this generation profile is representative for the system lifetime meaning no additional randomization of factors like cloud coverage, soiling and weather are used except for off course the yearly degradation of the PV modules.

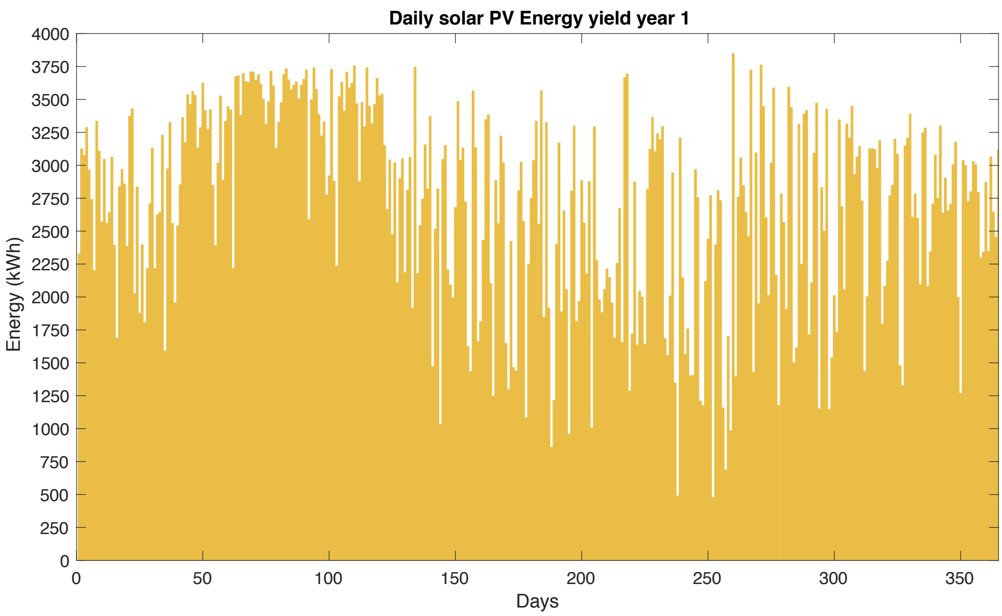


Figure 5.4 Daily energy yield of solar PV component in year 1, at 661.5 kWp installed capacity

Looking at the daily generation profiles as can be seen in Figure 5.5, the best, worst and average day generation remains fairly steady in its timing between 5:00 and 18:00 only differing in intensity. The difference between the best- and worst-case generation is 3368.8 [kWh] with a peak power difference of 447.82 [kW]. In the scope of reliability this could mean the difference between peak load coverage and insufficient power deliver increasing the importance of a secondary source or storage. The timing and frequency of worst case or best-case generation is not easily predicted since it is reliant on multiple short-term factors such as temperature, cloud coverage, soiling and other weather factors. It can however be stated that any increase of generation of PV which is above the required energy demand should be paired with an increase in storage capacity for it to be effectively used for later load satisfaction.

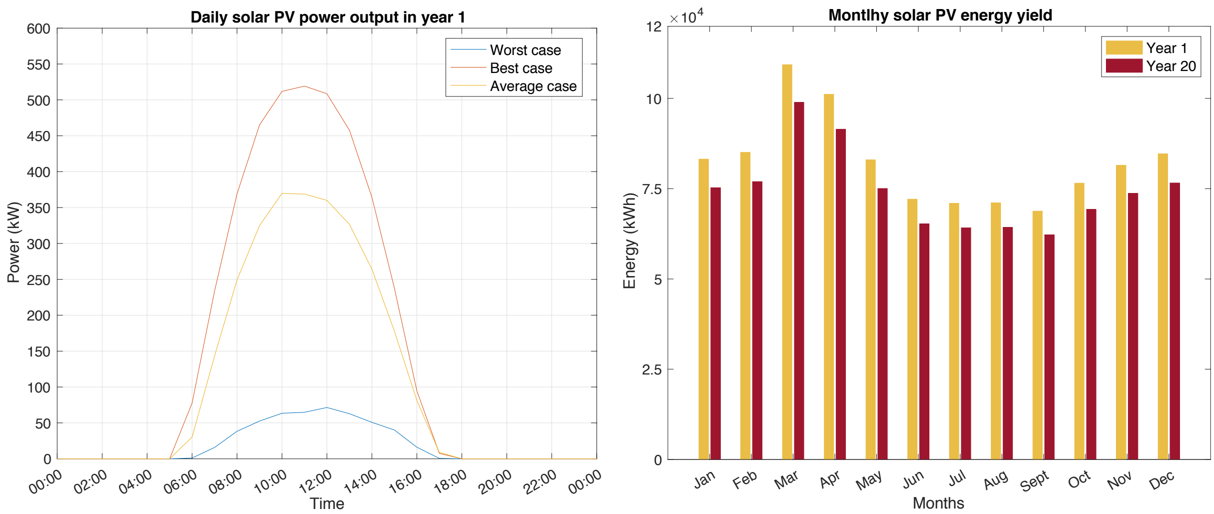


Figure 5.5 At 661.5 kWp installed Solar PV capacity; Daily solar PV generation for best, average and worst day scenarios (left); monthly energy yield for year 1 and year 20 (right)

Due to the performance degradation of 0.5 [%/year] the generation capacity of the solar PV component and thus the energy yield between year 1 and system lifetime end in year 20 will differ up to 9.5 [%]. The evolution of the monthly yield however follows the same pattern since the same input data is used for the entire system lifetime.

5.3 Combined generation and intermittency

The PV generation characteristics now combined with the tidal generation and load profile (discussed in section 4.2) provides insight into the operational reliability and operational range of the entire energy system at certain installed capacity. Figure 5.6 shows the best and worst-case generation of solar PV and tidal stream versus the load of year 1. Clearly there is a large difference in the system's ability to provide the required power depending on the generation ranges and timing of each component.

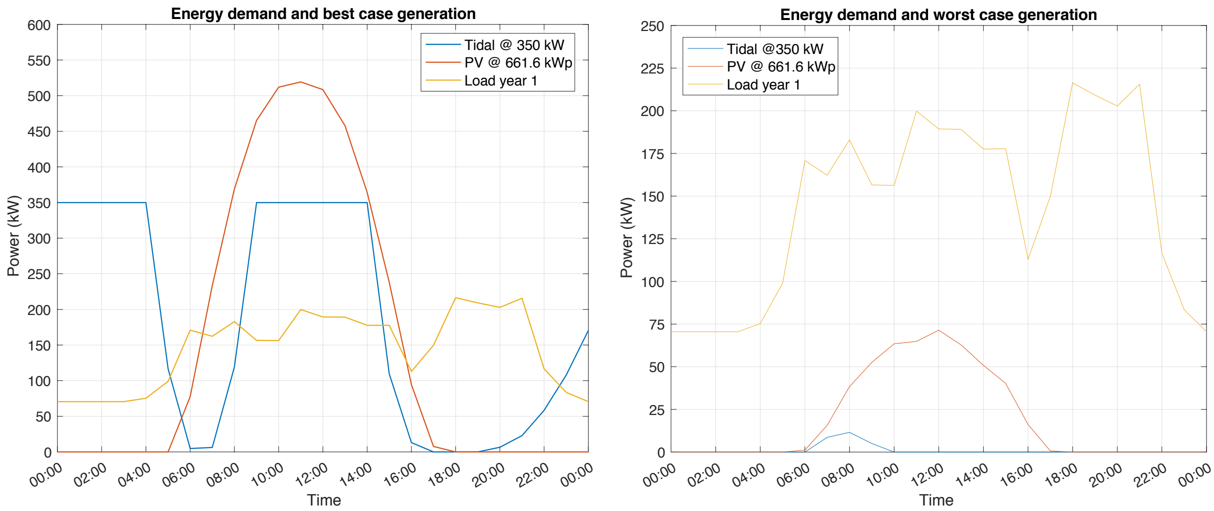


Figure 5.6 Best-case generation profiles of tidal stream and solar PV vs load (left); Worst-case generation profiles of tidal stream and solar PV vs load

A combined best-case generation of 4764 [kWh] and worst case of [483] shows almost a 90% decrease between the two scenarios and the possible overproduction, not taking into account the function of a BESS. After an intermittency analysis of the hourly generation profiles of year 1 it was however found that the worst- and best-case generation scenarios of PV and tidal did not coincide, this would lead to an oversized system if aim was to size for worst case scenario however, due to the intermittency factors at play for solar PV and tidal stream this scenario is never completely excluded. Best is thus to use the combined generation of the entire year and analyse the system ability to satisfy any energy demand in the actual simulation. It can however already be stated that the specific energy yield of tidal is higher than that of PV due to the longer operational window (Figure 5.7). The monthly specific energy values follow the yearly trends in generation of both PV and tidal respectively indicating June and November to be among the months with the lowest effective energy production.

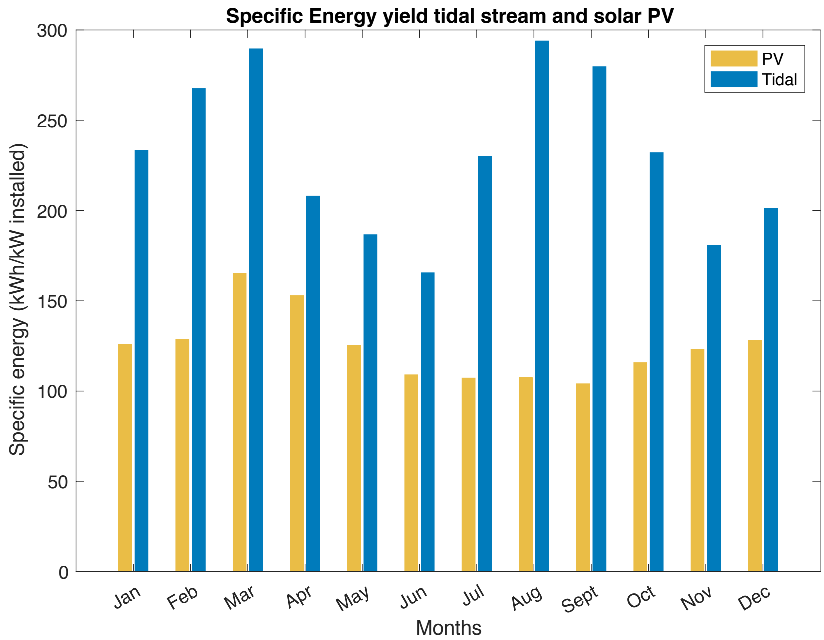


Figure 5.7 Specific energy yield of tidal stream and solar PV per month of year 1, indicating technical preference for tidal energy generation in relation to its effective installed capacity

When looking at the generation of 2 (random) days of approximately equal energy yield, May 27th and August 21st in Figure 5.8, it can be seen that the complementarity of both components differs and can influence the effective energy yield per hour creating different mismatches with the load demand. In the area of Panlaitan these intermittency differences and fluctuations in available energy create more complexity in the operational performance of the energy system, thus relying more on the functionality and size of the BESS.

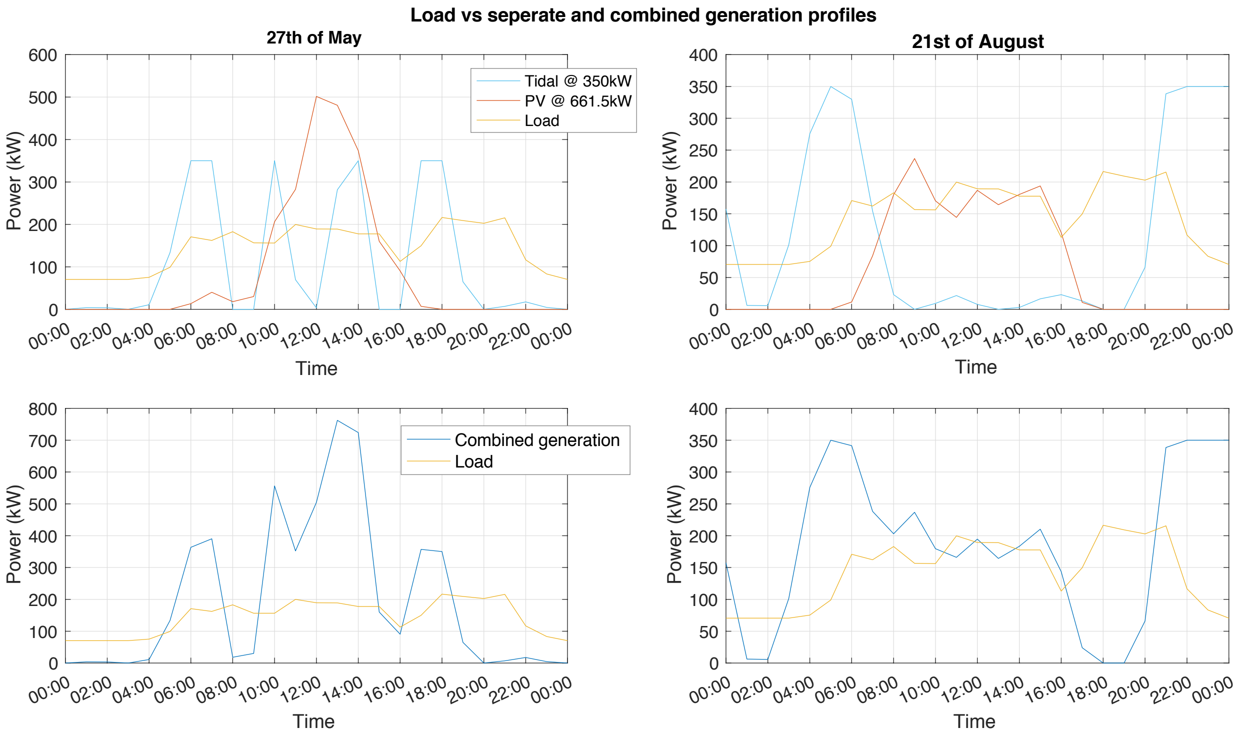


Figure 5.8 Complementary and combined generation

Figure 5.9 shows the combined generation, individual generation and battery energy level vs the unmet load. A correlation can be made between the decrease or absence of tidal energy generation and the lower battery level (or more capacity used from the battery). The periods with an energy shortage mostly occur during low tidal generation and not necessarily during low PV generation, indicating there is a more stressing relation between the generation timing of tidal energy and a higher reliance on the BESS. A larger battery that could store any excess energy could decrease any unmet load during low tidal production or absence of PV generation. Table 5.1 summarizes some generation values for each component at certain indicated installed capacity and the combined yield to show the difference in energy yield for both cases.

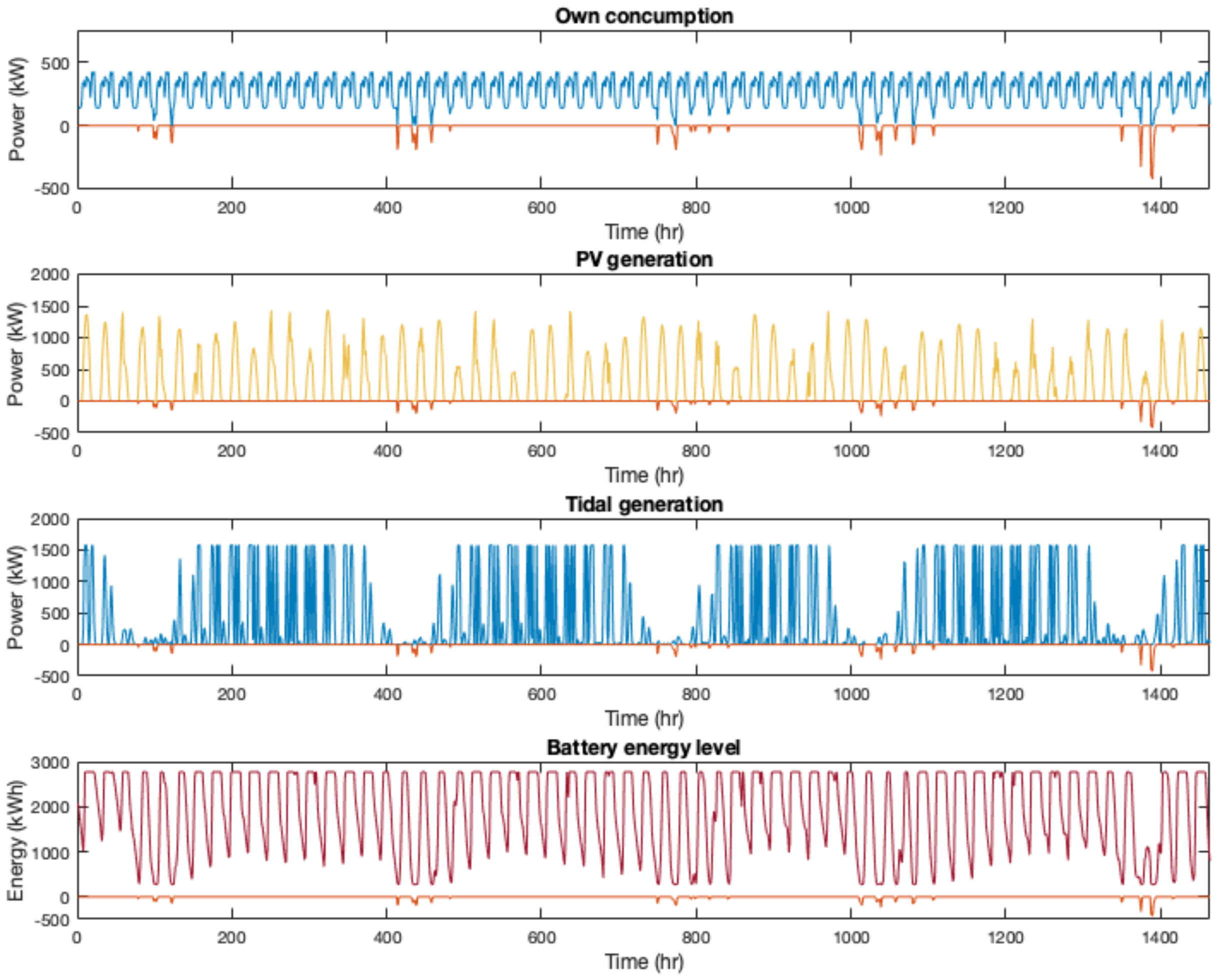


Figure 5.9 (Combined) generation profiles and battery energy level vs unmet load for a 2-month period (for Tidal @ 1750kW, PV @ 2079kWp and 3325 kWh BESS)

Table 5.1 Energy yield of Tidal stream and solar PV

Daily Generation case in year 20	Best case energy yield (kWh)	Worst case energy yield (kWh)
PV @661.5 [kW]	3479.96	478.09
Tidal @350 [kW]	896.58	4.33
Combined installed capacity 1011.5 [kW]	4376.54	482.42

A general strategy can be deducted from the generation profiles seen above. The increase of tidal energy generation could have larger effect on reliability increase without BESS increase, however from a certain point increase of the BESS capacity under the generation capacity is required for a positive reliability effect. The most pressing matter in the performance of this type of energy system is thus the complimentary nature of the generation components and their combined relation to the load curve. Mapping these aspects of a project can clarify effectivity and feasibility for such a system at a certain location. From a certain installed capacity of generation components, the effects of reliability improvement will show to level since there are a limited number of time periods in which both solar PV and TS have insufficient generation despite sufficient installed capacities. This can be due to the unavailability of irradiation for solar PV and slack water or neap tide conditions for Tidal stream. Since the total energy yield during the year is more than sufficient, an increase in BESS size could increase the autonomy of the system during these pressing hours of operation. However, this might not turn out to be the most (cost) effective usage for the BESS capacity covering relatively small periods of under production throughout the year.

5.4 Key performance indicators of conventional hybrid system

For baseline comparison the conventional system for Panlaitan was modelled using the original inhouse WEG excel model. An overview of the performance of the conventional system can be seen in Table 5.2. It shows the LOL, LOLH, OC and LCOE deducted from the simulation results. Additionally, the diesel energy share in year 20 is given to indicate the reduction of the RE share in the energy mix from 59.3 [%] in year 1 to 35.3 [%] in year 20. Even with the majority of diesel generated energy in the energy mix and higher related OPEX, the LCOE is at a relatively low value of 0.37 [$/kWh].

The Own consumption rate of 100[%] of the PV generated energy in year 20 shows that all RE is either consumed at time of generation or stored in the BESS. The control of this system is based on a load following dispatch control meaning the diesel generators will only be activated when the capacity of solar PV + BESS is insufficient, but will not be used to actively charge the BESS, minimizing unnecessary diesel energy production and thus increasing the effective use of the renewable energy share.

In conclusion it can be said that the LCOE of the conventional hybrid system is a benchmark to which the fully renewable systems are compared for their financial feasibility and the technical reliability values as discussed in section 3.1.4 are used for any technical assessment. The LOL of 0 [kWh] of the conventional system is due to the dependable capacity considerations made by WEG. As explained the dependable capacity in a fully renewable system with intermittent sources cannot be defined in a similar way and is more reliant on the BESS capacity.

Table 5.2 Conventional hybrid system simulation results in year 20

Configuration marker (conventional)	**PV installed capacity (kWp)**	**Diesel installed capacity (kW)**	**BESS capacity (kWh)**	**LOL kWh)**	**LOLH (hr/year)**	**OC (of PV generation) (%)**	**Diesel share on energy supply (%)**	**LCOE ($/kWh)**
Con-1	661.5	600	870	0	0	100	64.7%	0.366

5.5 Key performance indicators of FRES simulation in WEG Excel model

An overview of the performance of multiple configurations of the fully renewable hybrid system, selected among the 120 configurations simulated in the exhaustive search method, can be seen in Table 5.3. It shows the LOL, LOLH, OC and LCOE deducted from the simulation results. The RE share of this system is logically 100 [%], however, in contrary to the conventional system an acceptable LOL is assumed. The increase of necessary installed generation capacity due to the absence of a fully controllable dependable capacity like a GenSet creates an increase of required BESS capacity to meet the minimal accepted LOL value of 1 [%] (25255 kWh) of total yearly energy demand of 2525 [MWh]. The reduced OC rate is consequence of the larger installed generation capacity and mismatch of generation with energy demand. An increase of BESS would increase the OC and lower LOL till 0 [kWh] assuming all required energy can be stored and used at the required power output of the BESS for load satisfaction. In this way the combination of intermittent energy generation and the BESS storage capacity functions as the dependable capacity of the FRES.

The LCOE of the commercially most feasible system (D-5.5) is significantly higher than that of the conventional system. However, considering the large increase in CAPEX and reduction or removal of the high OPEX of diesel fuel, the LCOE is largely determined by these upfront investments for which cost reduction can be expected in the (near) future.

Table 5.3 Fully renewable hybrid system simulation optimal configurations and KPI values in year 20

Configuration marker (PV-BESS.Tidal)	PV installed capacity (kWp)	Tidal installed capacity (kW)	BESS capacity (kWh)	LOL (kWh)	LOLH (hr/year)	OC (of total generation) (%)	LCOE ($/kWh)
D-5.5	2079	1750	3325	23564.72	181	36.2	0.5395
F-5.4	2646	1400	3325	22447.66	191	36.8	0.5396
C-5.6	1795.5	2100	3325	23085.88	168	33.9	0.5548
E-4.8	2362.5	2800	2850	24483.33	211	25.4	0.6360
F-4.8	2646	2800	2850	22738.37	203	24.5	0.6536

The LCOE of all simulated configurations remains within a range of 0.28 – 0.66 [$/kWh] with over a 345 [%] increase of generation capacity between minimum and maximum configurations. The effects of the increase and decrease of the component variables on the LCOE and LOL can be seen in Figure 5.10. Notice the x-axis which indicates the LOL is here reversed from high to low values. The curves are of a configuration with either a fixed capacity of 1750 [kW] Tidal stream capacity, 2079 [kWp] solar PV or 2850 [kWh] BESS. In each curve 2 variables were kept constant with 1 varying within the predetermined range as indicated in the graph. The change in LCOE with increasing BESS capacity (and lower LOL values) is less steep than that of the PV and Tidal stream, however, starts at a higher value due to the high capital cost and required initial capacity. The curves for solar PV and Tidal stream increase follow the same shape however Tidal stream has a bigger effect on the reliability improvement (larger range for LOL) due to its generation outside of the daytime window and solar PV generation, which can directly influence the load satisfaction at those times without necessity for storage. The LOL decrease due to tidal and PV increase stagnates at increasing capacity due to the generation and load mismatch effects. Without a complementary increase in BESS an increase of generation capacity has lower influence on the performance. Yet significant increase of the LCOE is coupled to the increase in capacity after the required generation capacity and energy yield is reached. Any further increase of generation capacity only marginally improves the system reliability. This again shows the importance of the dependable BESS capacity necessary for reliability improvement of a FRES.

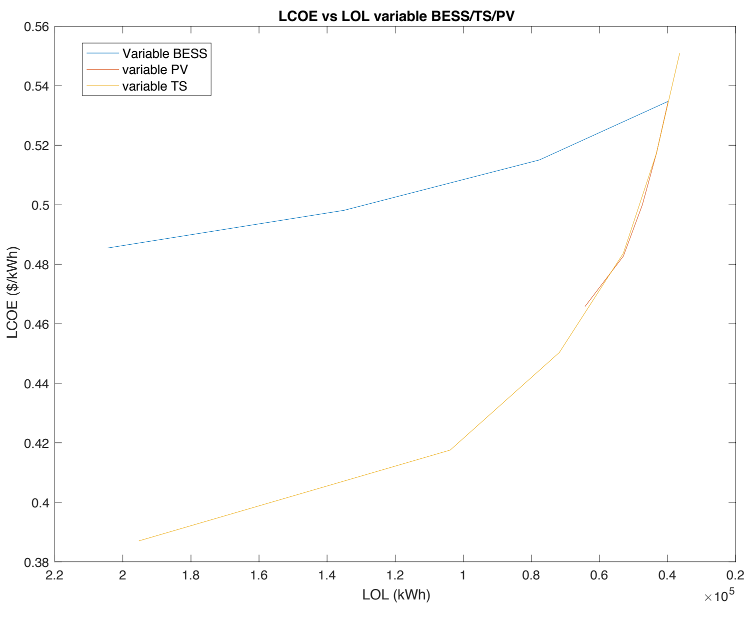


Figure 5.10 LCOE and LOL variation due to increase of system components

Looking at the system wide results from the Excel simulations multiple levels of LCOE change over installed capacity can be seen in Figure 5.11. The benchmark value of the conventional system is indicated. It is clear that most system configurations fall out of the acceptable/preferred region and only few operate within the technical limit of max 1 [%] LOL as seen on Figure 5.12. In Figure 5.13 a LOLH limit is indicated for both 288 [hr/year] or 12 days a year and 1 [%] (87.6 hr) per year. It shows that according to the WEG model the intermittency behaviour and complementary generation is still very frequent even though a technical sufficient system is found. This can be improved with an increase in BESS as mentioned.

As expected, the own consumption rate decreases and levels out with a significant increase in installed generation capacity considering the overgeneration. At an installed capacity of solar PV of around 1230 [kWp] and Tidal stream capacity of 700 [kW], the year 20 combined energy yield of 2838 [MWh] is already sufficient to cover the required year 20 energy demand of 2525 [MWh], not considering mismatch. In the accepted systems described in Table 5.3 the total annual generation varies between 7643 [MWh] and [10530 MWh]. Considering now the mismatch characteristics as explained in section 5.3, even with a (large) BESS the effective energy use or own consumption rate does not equally increase with capacity due to the maximum energy demand in year 20 (Figure 5.14). The overproduction is not used and cannot be fed back into a grid since this is an isolated system. Additionally, It can be seen that most configurations, even with higher installed capacities do not meet the reliability (LOL) requirement (Figure 5.12). The LOLH follows a similar scatter pattern as that of the LOL, since an increase in LOL parallels an increase of LOLH and vice versa. Most combinations of components also fall above the conventional LCOE benchmark indicating a relatively ineffective implementation of TS for this case.

The installed BESS capacity is represented in the multiple layers within the scatterplots and shows that mainly due to the effective BESS capacity can the system be made fully reliable. The influence of hourly generation capacity, unlike with the conventional diesel generation component, loses its relevance for the reliability.

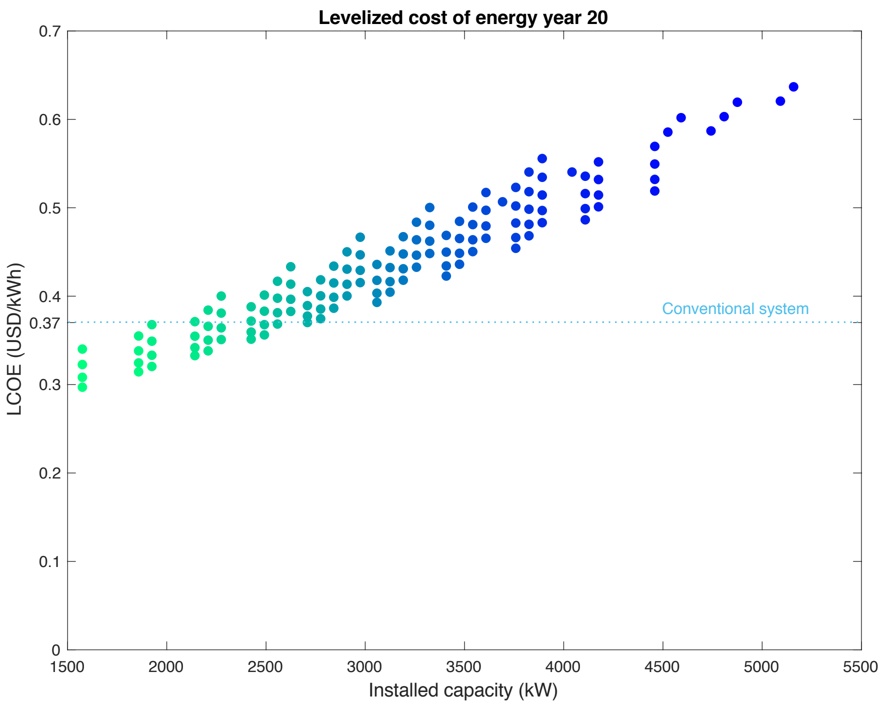


Figure 5.11 LCOE vs installed capacity

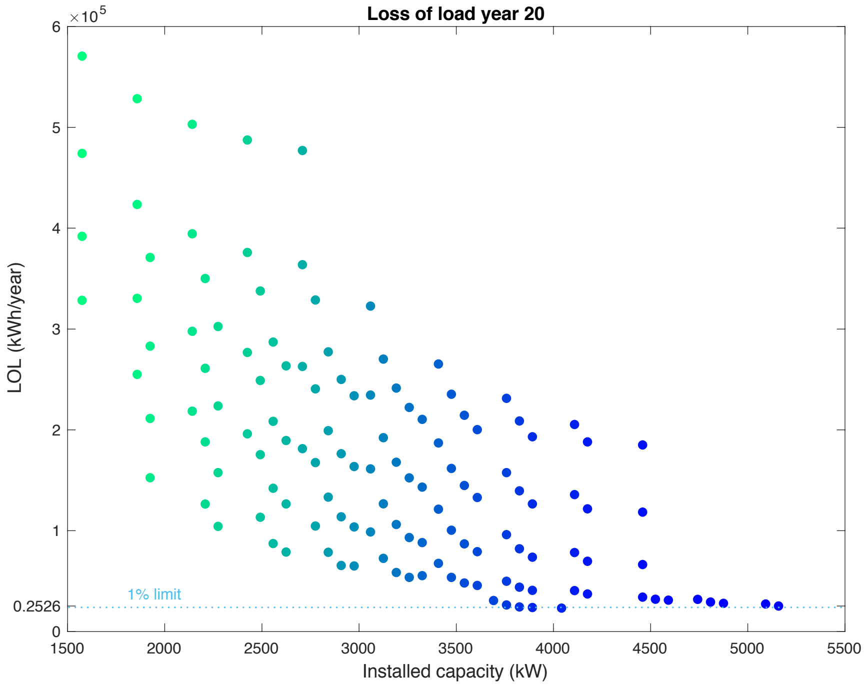


Figure 5.12 LOL vs installed capacity

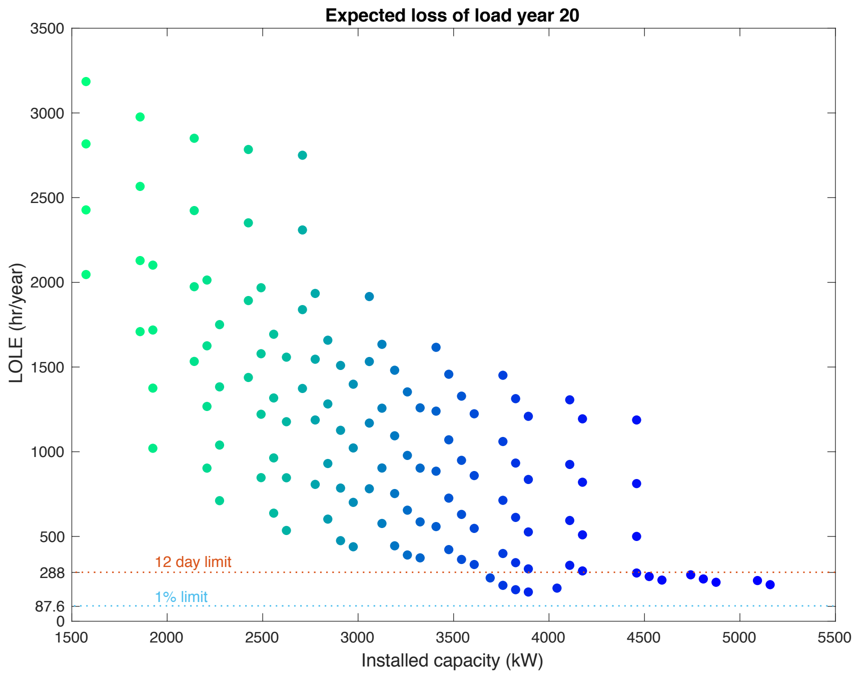


Figure 5.13 LOLH vs installed capacity

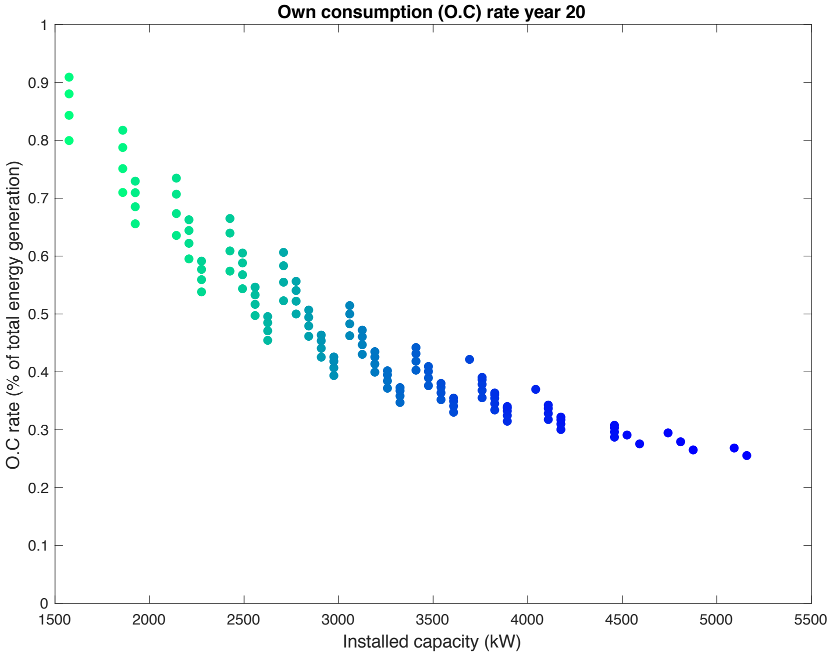


Figure 5.14 OC rate vs installed capacity

5.6 Additional results

From

Figure 5.15 it can be seen that installing the entire generation capacity in the beginning of the project lifetime is inefficient. This figure was generated with the energy yield and own consumption of configuration D-5.5. It shows a large overproduction which can contribute to earlier component maintenance or replacement. A segmented instalment is thus required which does not follow the prementioned Philippine regulation. Figure 5.16 indicates there is a limited own consumption that can be reached when no BESS is introduced compared to the satisfied load coverage including a BESS. Simply increasing the (relatively cheaper) generation components will thus not necessarily lead to a cheaper and more reliable system.

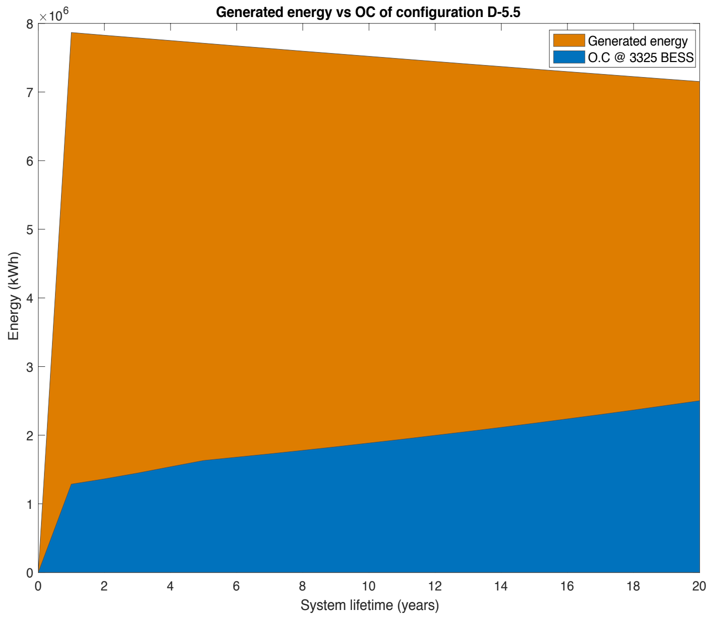


Figure 5.15 Total energy yield vs Own consumption of configuration D-5.5

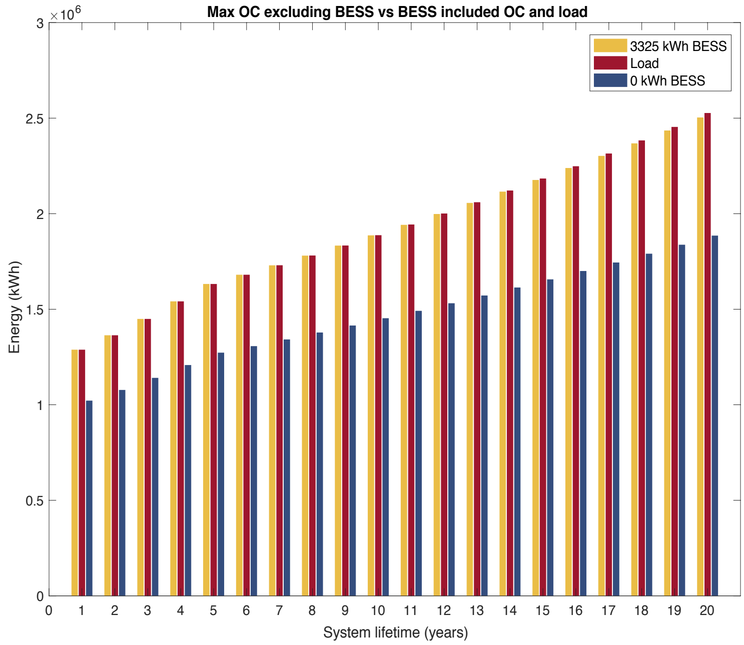


Figure 5.16 Maximum OC potential excluding BESS compared to OC with BESS for configuration D-5.5

5.7 Key performance indicators of HOMER-pro FRES simulation

From the optimization done in HOMER-pro the results are aimed at providing results of a more thorough simulation set as reference to the Excel model, for sensitivity analysis purposes and form a reliable basis up on which conclusion can be drawn on the optimal system configuration and its accompanying costs. The HOMER-pro optimization is based on 702.240 simulations over the system lifetime of which 10.149 were infeasible due to capacity shortage constraints. 488.892 were omitted due to multi-year infeasible solutions, insufficient or lack of generation capacity (e.g. BESS only) and converter mismatches. Of the remaining 203.199 simulations 1 configuration was selected for each sensitivity case as most optimal for the reliability conditions described in section 4.4. The results of the optimization are given in Table 5.4.

The RE share of this system is again logically 100%, however. Since HOMER-pro optimizes for NPC it is required to manually select the configuration with the lowest or desired LCOE since this is the performance indicator used for this study. However, for a fully renewable energy system of which most costs are initial capital expenditures, it showed that the system with the lowest NPC was also the system with lowest LCOE.

Table 5.4 HOMER-pro optimal configuration and KPI values in year 20

Unit architecture denotation (PV. BESS.TS)	Solar PV installed capacity (kWp)	Tidal stream installed capacity (kW)	BESS capacity (kWh)	Capacity shortage (kWh)	OC (of total generation) (%)	Loss of Load hours	LCOE ($/kWh)
22.16.10	2079	700	3360	25941.73	46.92	1900	0.4552

This already shows a more desirable outcome for the FRES with a LCOE of 0.45 [$/kWh] closer to the conventional benchmark value of 0.37 [$/kWh]. The capacity shortage remains within the acceptable range and a higher own consumption rate is achieved. The dominant generation component here is solar PV with a smaller secondary generation of Tidal stream complemented with a fairly similar size BESS as resulted from the Excel simulations. Indicating a similar configuration strategy as with the exhaustive search. The sample size for the optimization in HOMER-pro was much larger than that of the Excel based model, creating clearer trends and providing more data to make correlations between the components and indicators. Additionally, the KPI's were plotted against both the Installed generation capacity and the BESS capacity (Appendix J) as to show its influence on reliability. The benchmark conventional system limits have not been indicated since every solution presented here is considered to provide the required reliability.

Looking at the system wide results again multiple levels of LCOE change over installed capacity can be seen in Figure 5.17. Due to the larger sample size a clear optimality can be found in the boundary LCOE values at an installed generation capacity of 2779 [kW] which is 1050 [kW] lower than the system found in the Excel model of section 5.5. a more efficient energy use is achieved here due to the larger BESS size compared within this optimal configuration confirming the previous correlation of BESS and effective energy use or OC increase. Due to this the LOL shows a sharper decrease up to the installed capacity of this optimal configuration in Figure 5.18. Configurations with lower BESS capacities would cause the LOL value to increase at constant installed generation capacity. Similarly, to the Excel results the OC rate of Figure 5.19 shows a decreasing and levelling trend with increasing installed capacity, confirming the ineffectiveness of generation capacity increase after 2779 [kW] at sufficient BESS.

The overproduction of this system is lower in comparison yet still significant with an OC rate of 46 [%]. Again, this energy is not used and cannot be fed back into a grid. The LOLH was not given within the HOMER-pro results, however from hourly mismatch analysis performed it was found to have a value of 1900 hours in which demand was larger than generation, yet of each of small quantity.

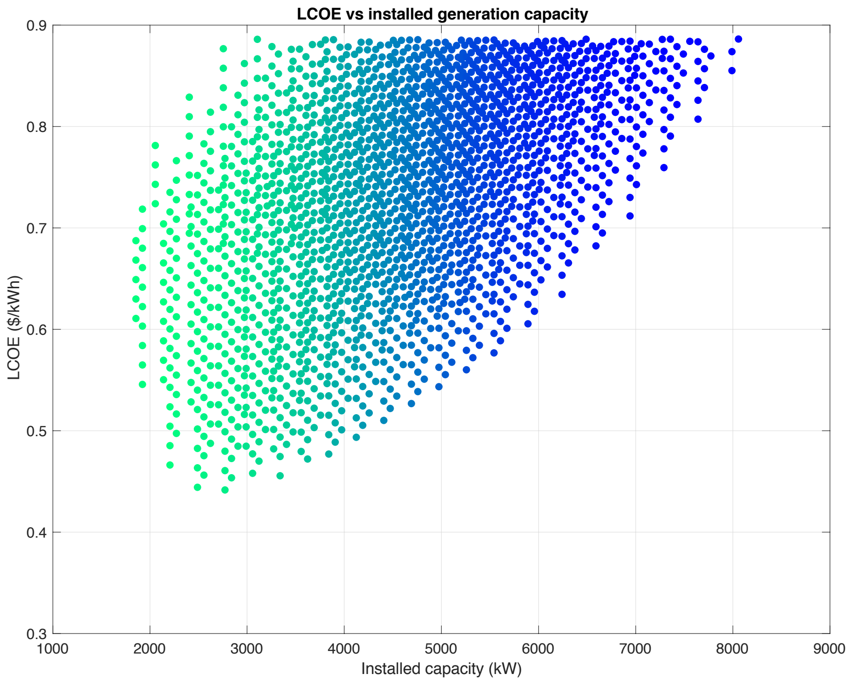


Figure 5.17 LCOE vs installed generation capacity from HOMER-pro optimization

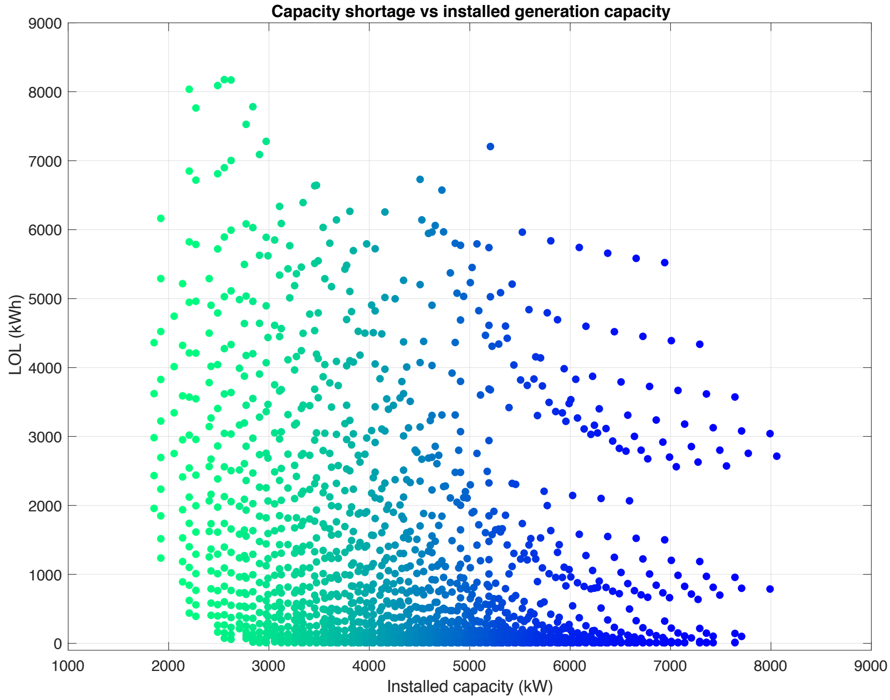


Figure 5.18 Capacity shortage (LOL) vs installed generation capacity

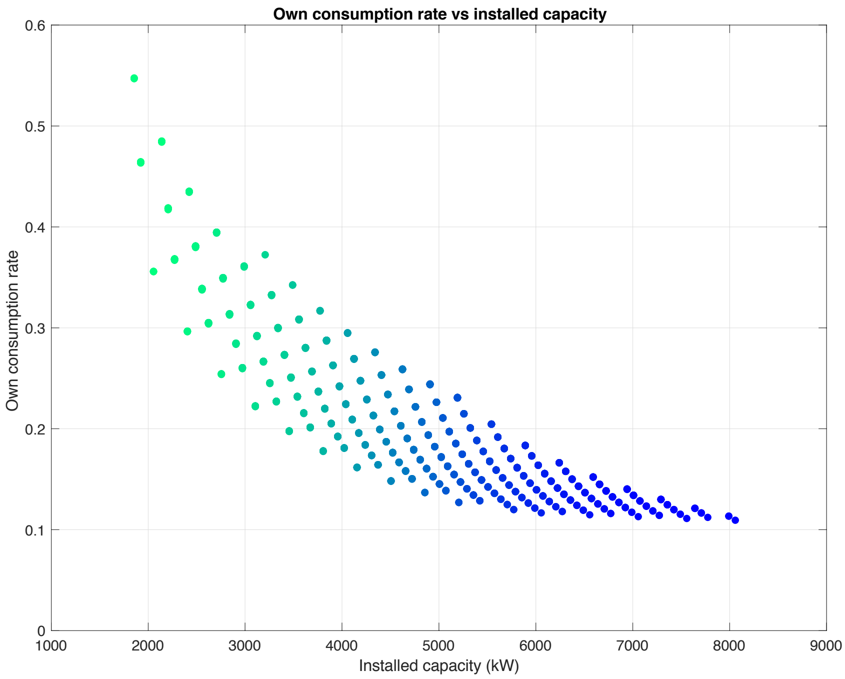


Figure 5.19 Own consumption rate (of total generated energy) vs installed generation capacity in HOMER-pro optimization

5.8 Scenario performance

To investigate the sensitivity of the FRES in relation to the Reliability limit (LOL) and cost additional optimizations were done in HOMER-pro for multiple cases of capacity shortage limits and tidal stream cost/kW installed as shown in

Table 5.5. A lowering in capacity shortage limit by a factor 100 significantly lowered the FRES OC value from 47 [%] to 27 [%] yet a slight increase of 4 [%] paired with significant increase in generation capacity. This in turn also influenced the LCOE due to lower effective energy consumption compared to total installed component capacities and total energy yield. This again has to do with the unavoidable time periods of insufficient generation of both solar PV and tidal stream, and full reliance on the BESS performance with its limited capacity. The lower LOLH values indicate more frequent coverage of hourly demand. However, the size of energy shortages can differ significantly due to the fluctuating generation meaning there will be similar frequencies for shortages even with larger installed generation and storage capacities.

The variation of tidal stream cost solely has an effect on the LCOE and shows smaller relative changes in LCOE between configurations with similar component architectures. Even with cost changes, the optimization finds little effectiveness in change of tidal stream installed capacity for the LCOE or OC of the FRES, again indicating the limited range of effective energy generation for load coverage.

To conclude, the sensitivity of an FRES system cost thus depends largely on the reliability requirements effective energy use, combined with the larger installed BESS capacity and less on the actual cost of tidal turbine installed capacity due to the specific generation and load mismatch. The longer operational time (even if predictable) does not necessarily benefit the complementary function of TS with solar PV in this FRES for this location. Generally, one of the most important factors to consider is thus the complementarity of the tidal intermittency with the solar PV intermittency and the accuracy of the load distribution.

Table 5.5 Sensitivity study results for capacity shortage and tidal stream cost variation in HOMER-pro

Capacity shortage limit (%)	Tidal stream cost (USD/kW)	Solar PV inst (kWp)	Tidal stream inst (kW)	Total installed inst (kW)	BESS capacity (kWh)	Total generation year 20 (kWh)	Loss of Load (kWh/yr)	OC (% of total generation)	Loss of Load Hours (hr/yr)	LCOE ($/kWh)
1	1500	2079	700	2779	3360	5338810	25941.73	47%	1900	0.4260
1	1750	2079	700	2779	3360	5338810	25941.73	47%	1900	0.4552
1	2000	2079	700	2779	3360	5338810	25941.73	47%	1900	0.4693
1	2250	2079	700	2779	3360	5338810	25941.73	47%	1900	0.4836
1	2500	2079	700	2779	3360	5338810	25941.73	47%	1900	0.4409
0.1	1500	4064	700	4764	3780	8367815	4530.35	30%	1771	0.5614
0.1	1750	4064	700	4764	3780	8367815	4530.35	30%	1771	0.5905
0.1	2000	4064	700	4764	3780	8367815	4530.35	30%	1771	0.6046
0.1	2250	4064	700	4764	3780	8367815	4530.35	30%	1771	0.6188
0.1	2500	4064	700	4764	3780	8367815	4530.35	30%	1771	0.5763
0.01	1500	4630	700	5330	3780	9233245	2406.33	27%	1753	0.5948
0.01	1750	4630	700	5330	3780	9233245	2406.33	27%	1753	0.6239
0.01	2000	4630	700	5330	3780	9233245	2406.33	27%	1753	0.6338
0.01	2250	4630	350	4980	5040	8150462	2732.92	31%	2023	0.6409
0.01	2500	4630	350	4980	5040	8150462	2732.92	31%	2023	0.6097

6

Conclusions

A number of research questions were formulated to aid in the feasibility frame working and assessment for this study. This chapter will cover the conclusions based on the content created for the case study of Panlaitan and general implementation of tidal stream turbine technology in FRES for rural island electrification. Sections 6.1, 6.2 and 6.3 will discuss the elements in relation to the 4 sub questions formulated in section 1.3.2 and the specifics for the energy system optimization performed for Panlaitan. Section 6.4 will address more broad conclusions regarding tidal stream energy implementations.

6.1 FRES necessity and tidal energy potential for implementation in The Philippines

To indicate the necessity of introducing the intended FRES for rural island electrification in the Philippines, the current status and barriers of electrification were discussed in section 2.1. Larger islands are connected through electricity grids, yet smaller islands are often not included in any grid expansion and remain dependent on the existing fossil fuel infrastructure and its related cost for energy generation. This is paired with lack of expertise and resources to provide sufficient and reliable amounts of electricity leading to frequent shortages or complete absence of access to electricity. Since most of The Philippine's electricity is generated using conventional fossil fuelled systems it is clear any introduction of RES would aid a more sustainable pathway, which is in line with both international agreements (Paris agreement) and the WEG objective.

Island electrification requires a customized autonomous solution to overcome the barriers of isolation reliability (of supply). A RES forms a local source of electricity and provides independence from the fuel infrastructure and its relatively high fluctuating costs for fossil fuelled generation. When working with renewable energy sources the intermittent nature as found, increases complexity of operation and integration of multiple system components. A fully controllable dependable energy source as diesel energy generation is usually included to ensure reliable energy supply. Additionally, the expertise and resources to design, operate and maintain RE systems in rural areas are not available, creating the opportunity and necessity for involvement of companies such as WEG. Seeing the global potential of ocean energy and in particular tidal energy (3 TW), combined with the access of this resource in island environments, this forms a viable option for implementation in isolated (hybrid) energy systems and initiated this study.

6.2 Method and performance indicators for feasibility analysis

The feasibility assessment approaches, strategies, performance indicators and tools were discussed in section 2.2 in order to select the ones most suitable for this study. Technical performance and reliability were prioritized above financial feasibility as to exclude ineffective configurations within any simulation or optimization. Cost considerations would follow for configurations able to provide the required energy and reliability.

The LOL was selected as the main reliability indicator representing the shortage of load satisfaction. Together with the LOLH and OC the frequency of power shortage and effective energy use could be assessed. The LCOE of the system was used as the main financial performance indicator due to its enveloping nature for full system lifetime evaluation. As a baseline comparison the KPI values for a conventional HRES were used as designed for the same case location of Panlaitan.

A (generic) framework was designed to describe the full process of tidal stream energy implementation assessment based on the content of sections 2.2, 2.3, 2.4 and the research objectives. This framework was subsequently successfully used for the assessment of the case study for Panlaitan.

A WEG Excel based model was adapted to account for the secondary tidal stream renewable energy source. This model was aimed towards providing flexibility in simulation and insight in system behaviour. However, a more thorough optimization was necessary to go over all possible configurations and system operational constraints including any sensitivity cases. For this the software HOMER-pro was used, both as an addition and validation to any data acquired through the WEG Excel based model as discussed in section 3.2.

For optimization purposes it was necessary to identify the system component working principles (section 2.4), collect or construct resource data (section 4.3) , identify energy demand (section 4.2) and as such define operational requirements. Integrated system behaviour could only be assessed when simulated for the entire system (lifetime). Individual component efficiency and (overall) behaviour could then be analysed by isolating and graphically presenting the intermittency or variability of (combined) generation and energy yield (chapter 5).

6.3 Technical and commercial feasibility for Panlaitan

Following from the Excel based simulations it can be concluded that the effective increase of solar PV and TS generation capacity reaches a limit due to mismatch of hourly generation and load caused by intermittent generation and the semi-dependable (time limited) capacity of the BESS shown in sections 5.3. Any increase of generation should be paired with an effective increase of BESS limited to full energy demand coverage. The BESS shows to be the most crucial component when it comes to the reliability in this system.

For tidal stream implementation the relation between the tidal system, the available power and the cyclical nature of availability determine the effectiveness of its implementation as seen from sections 4.3.5 and 2.4.2 regarding the tidal turbine choice. Analysing these conditions for any location is thus crucial. To obtain the required current velocity data an assessment was made of the geographical and tidal system characteristics around Panlaitan. This was followed by a measurement expedition in which spot measurements were done using an ADCP (section 4.3). This resulted in a set of current velocity profiles from which it was concluded that the current velocity range found around Panlaitan was not in range of tidal turbine operational velocities and would only deliver an annual energy yield of approximately 8843.5 [kWh] at a capacity factor of 0.014, as such excluding this site from further tidal stream energy implementation. Using a STEM a current velocity dataset was made representing a similar tidal system with higher energy potential, which was used for further simulations.

As discussed, the dependable capacity of a GenSet cannot simply be replaced by tidal turbines. Even if predictable, the power output is not controllable or always of the required amount fluctuating between the maximum and minimum daily yield for a single turbine of 896 and 4 [kWh]. Any shortcomings have been identified to appear around Neap tide or slack water conditions.

For solar PV generation the shorter-term intermittency creates uncertainty in availability which can fluctuate between a maximum and minimum daily yield of 3846 and 478 [kWh] (at 661.5 kWp installed). It relies more on the BESS's complementary functionality. An increase of this generation above require energy levels during the solar PV generation window (daytime) would only be effective if paired with increased BESS capacity, in contrary to tidal energy which can generate in a larger timeframe and satisfy any load requirements outside daytime, resulting in a higher specific energy per installed [kW].

Clearly there is a large difference in the two system's ability to provide the required power. In the area of Panlaitan these intermittency differences and fluctuations in available energy show that the two sources do not necessarily effectively complement each other (section 5.3). Additionally, in any of these cases there is an acceptable level of LOL (1% or less) maintained, which in relation to the 0 [kWh] LOL of a conventional system would already exclude competitiveness of the FRES.

The LCOE of all simulated configurations remains within a range of 0.28 – 0.66 [$/kWh] with over a 345 [%] increase of generation capacity. However, the LCOE of the systems that meet the reliability conditions are not in range of any conventional or competitive value. Additionally, to avoid large overgeneration a segmented instalment is preferred although not always more financially beneficial.

The optimization performed in HOMER-pro shows a more desirable outcome for the FRES LCOE of 0.45 [$/kWh] closer to the conventional benchmark value of 0.37 [$/kWh] (yet still not competitive) already excluding any configurations that did not meet reliability requirements. Due to the larger sample size a clearer optimality can be found in the boundary LCOE and LOL values (section 5.7) at an installed generation capacity of 2779 [kW], which is 1050 [kW] lower than the system found in the Excel model of section 5.5. Even with the identical step size for each component used in both Excel and HOMER-pro, a more efficient energy use is achieved here due to the larger BESS size, and most likely also the different solar PV irradiation data (HOMER-pro database).

A lowering in capacity shortage limit by a factor 100 significantly lowered the FRES OC value from 47 [%] to 27 [%]. This in turn also influenced the LCOE due to lower effective energy consumption compared to total energy yield. Changes in tidal stream costs only marginally influenced the LCOE of the entire system. The sensitivity of an FRES system's costs thus depends mostly on the reliability requirements in place. The longer operational window of TS (even if predictable) does not necessarily benefit the complementary function of TS with solar PV in this FRES for this location.

Generally, one of the most important factors to consider is thus the complementarity of the tidal intermittency with the solar PV intermittency and the accuracy of the load distribution.

The absence of a fully controllable capacity replaced with tidal stream energy shifted the importance of functionality from a single component (GenSet) to the complementarity of all 3 generation and storage components present in this FRES. This considered, a direct replacement of GenSets with TS turbines assuming a baseload generation is not possible

The implementation of tidal stream energy for the island of Panlaitan was excluded due to the tidal conditions as measured in section 4.3. However, in the hypothetical case of tidal scenario 3 the generation potential over the system lifetime shows to be sufficient, as well as the potential of solar PV. However, due to the variability of the tidal power output throughout its daily, monthly and yearly cycles the system requires significant increases in installed generation capacity and BESS capacity in order to maintain its reliability. The related LCOE and thus financial feasibility also shows a negative result for the implementations as not being cheaper or competitive to the conventional system. Only based on the local conditions can the combination of these two RES be validated. For the case of Panlaitan, this tidal environment and combination of these resources was found to be insufficient.

6.4 Tidal stream energy feasibility as dependable resource in FRES

From the simulations performed in both Excel and HOMER more general conclusions can be draw for the implementation of tidal stream energy in hybrid energy systems for island electrification

- The local conditions need to be assessed thoroughly to give a realistic indication of the tidal stream potential due to the nature of its variability throughout locations on earth, its cyclical natural and phase shifts throughout the year, and the influence of local topography, bathymetry and weather conditions.
- If sufficient potential is found the nature of the tidal system dictates the timing and shape of generation. This should fall within a suitable profile in comparison with the solar PV generation at location and the load profile to be satisfied.
- In contrast with the dependable capacity of GenSets, renewable sources require a significant increase in installed capacity to compensate for the undependable renewable energy generation and thus also require a significant increase in BESS capacity to cover mismatch between load and generation.
- The current cost involved with tidal stream energy do not allow for competitive integration, however cost trends show a decrease in future cost of all related components, making the integrated system more competitive in future scenarios.

- The global potential of ocean kinetic (tidal stream) energy and the potential in the Philippines shows it can be considered as a significant and accessible energy source which is based on the inexhaustible source of constellational movement

To answer the main research question and conclude on the goal of this study:

'What is the technical and commercial feasibility of a solar PV, Tidal stream energy and BESS fully renewable hybrid energy system for small scale island electrification in the Philippines, considering the technical implications, local (economic) environment and demand?

Technically it is possible to integrate a more predictable source like tidal stream energy with PV to create a 100% renewable system for island electrification, however highly dependent on the tide system and complementary nature of the generation sources, which requires local data for accurate simulation. Factors such as the significantly large overproduction, the necessity for large BESS, the dependency on location and tidal climate make it a more difficult concept to realize within workable financial boundaries. As shown the LCOE, even with varying TS cost, is still not competitive with the conventional hybrid system. If a suitable tidal system and environment is found TS energy could function as a reliable base-load generation. In order to replace any dependable controllable capacity with a semi-dependable uncontrollable capacity the technical implications are still a challenge indeed. Tidal stream energy is however a renewable energy technology in the process of price reduction, increased deployment and has the potential to become a more competitive form of energy generation in the near future, following the price reduction trends of hydro and offshore wind. The financial feasibility as can be seen is highly dependent on the effective use (Cf) of each component. As the price will reduce, and the efficiency can still increase logic would suggest a point of feasibility should be possible for locations with better tidal system environments, more constant generation and a better complementary function with (higher) intermittent energy sources.

7

Recommendations

This study was performed for a specific site and under specific conditions related to both WEG and the TU Delft. Despite the comprehensive work performed in this assessment there are areas of improvement or further clarification. For further assessment of tidal stream implementation in FRES and improvements of the simulations, optimizations and sensitivity study performed the following recommendations are given for more inclusive or specific tidal stream energy implementation frame working and assessment.

7.1 Model and components

7.1.1 Turbine performance data

For most of the turbines assessed in this study limited specifications or test phase reports were available. Since the start of this study more information should now be available on the exact operational requirements and performance of the different turbine types. Additionally, system lifetime degradation values can be better estimated with more test sites and commercial projects in place.

7.1.2 Localized long-term data acquisition

For more precise power output calculations and a better representation of local tidal conditions the extrapolated STEM data can be replaced with actual measured data values for a long time period (1 or more lunar cycles) at the location of interest. In such a way a more precise estimation of local potential and integration possibilities can be made.

7.1.3 Coherent model and software usage

For the study performed multiple models were used or created using multiple software types. This can create inconsistencies in the processing of data or the comparison of values. For example, the PV generation values as used from PV sol in the Excel based model differs from the solar PV generation data used in HOMER-pro creating different power generation conditions in this software and ultimately influencing the results. Using an enveloping software or method specifically designed for the complete financial and technical assessment with flexibility for adaptation of all variables and parameters has thus the advantage of consistency and efficiency in optimization.

7.1.4 Detailed financial analysis

For a better financial feasibility assessment, a more in-depth analysis off all the related costs can be made. This includes elements like pre-feasibility research, design and conceptualisation phase, construction and transport, and company related price projections and profitability considerations. By making a more detailed financial analysis the competitive position of this FRES system can be improved or shown to be worse.

7.2 Future work

For tidal stream energy implementation in small scale energy systems designed for rural electrification there are some fields in which headway can be made.

Firstly, the cost estimations and tidal stream industry layout can be better analyzed and described for specifically the tidal stream energy sector, clearly distinguishing it from the current hydro or the general ocean energy terminology used to describe any potential in this sector. Organizations like NREL and IEA have previously avoided any distinction of this type of energy and have only recently began to include this type of RE in any prognoses or evaluations.

Secondly the available data on ocean currents, tidal system, and current velocity mapping in rural areas can be increased and improved to work on a smaller scale than global maps and general assumption. This will provide better insights in possible tidal potential reducing the necessity for time intensive local measurements. This is both a field that can be explored in the commercial sector as well as governmental.

The innovative aspect of tidal energy implementation does not necessarily lie in the mechanical aspects of the turbine technology but in the proper mapping of potential and control strategy development for combination of this predictable yet intermittent source with another RES.

Appendix A

Philippine energy statistics

DEPARTMENT OF ENERGY

2018 POWER STATISTICS

Gross Power Generation by Plant Type*

in MWh

LUZON	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	% Share
Coal	**15,814,345**	**14,351,121**	**15,548,335**	**14,653,275**	**14,099,158**	**14,417,796**	**13,503,727**	**14,091,376**	**20,046,584**	**19,681,127**	**21,877,501**	**25,755,945**	**27,346,492**	**29,679,511**	**33,143,458**	**33,952,671**	**37,362,128**	**51.4%**
Oil-based	**3,625,031**	**3,595,860**	**4,590,814**	**2,021,641**	**1,711,415**	**2,192,048**	**1,928,244**	**1,864,281**	**3,287,173**	**1,290,685**	**1,800,321**	**1,600,626**	**2,342,360**	**1,844,787**	**2,561,831**	**2,379,192**	**2,187,694**	**3.0%**
Combined Cycle	*748,450*	*438,755*	*738,437*	*90,608*	*238,870*	*652,834*	*513,442*	*638,520*	*1,202,040*	*123,556*	*227,354*	*247,159*	*514,980*	*275,892*	*693,685*	*405,022*	*522,115*	*0.7%*
Diesel	*2,166,500*	*2,317,101*	*2,688,194*	*1,910,774*	*1,315,067*	*1,348,033*	*952,751*	*594,559*	*1,003,383*	*890,321*	*1,099,123*	*1,183,466*	*1,520,521*	*1,483,116*	*1,622,749*	*1,692,212*	*1,520,177*	*2.1%*
Gas Turbine	*29,338*	*1,737*	*183*	*1,433*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*10,290*	*499*	*0*	*0*	*0.0%*
Oil Thermal	*680,743*	*838,268*	*1,164,000*	*18,826*	*157,478*	*191,182*	*462,051*	*631,203*	*1,081,749*	*276,807*	*473,844*	*170,001*	*306,859*	*75,489*	*244,898*	*281,958*	*145,402*	*0.2%*
Natural Gas	**8,770,851**	**13,139,410**	**12,384,467**	**16,860,917**	**16,365,960**	**18,789,414**	**19,575,855**	**19,886,827**	**19,517,854**	**20,591,323**	**19,641,527**	**18,783,471**	**18,685,808**	**18,877,915**	**19,853,783**	**20,547,239**	**21,333,789**	**29.3%**
Renewable Energy (RE)	**8,176,658**	**6,448,239**	**7,330,296**	**7,090,897**	**9,064,924**	**8,220,653**	**9,191,708**	**9,132,372**	**7,413,115**	**8,454,125**	**8,993,077**	**8,679,476**	**8,391,821**	**9,710,650**	**10,938,477**	**11,633,318**	**11,844,758**	**16.3%**
Geothermal	*5,276,171*	*2,600,465*	*3,033,417*	*2,742,203*	*3,519,417*	*3,600,503*	*3,729,921*	*3,515,964*	*3,323,495*	*3,485,813*	*3,588,417*	*3,398,601*	*3,817,330*	*4,096,454*	4,226,913	3,909,704	3,871,484	*5.3%*
Hydro	*2,900,487*	*3,847,774*	*4,296,879*	*4,331,224*	*5,492,271*	*4,562,309*	*5,400,402*	*5,549,227*	*4,013,529*	*4,836,470*	*5,292,482*	*5,155,521*	*4,357,160*	*4,768,825*	5,011,100	5,729,567	5,944,913	*8.2%*
Biomass	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*2,752*	*14,375*	*43,638*	*36,839*	*59,699*	*65,279*	*187,188*	438,807	598,665	593,968	*0.8%*
Solar	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*66,427*	494,946	495,984	503,131	*0.7%*
Wind	*0*	*0*	*0*	*17,469*	*53,235*	*57,842*	*61,386*	*64,428*	*61,717*	*88,204*	*75,339*	*65,655*	*152,052*	*591,756*	766,711	899,397	931,264	*1.3%*
Total Generation	**36,386,885**	**37,534,630**	**39,853,911**	**40,626,730**	**41,241,457**	**43,619,911**	**44,199,534**	**44,974,855**	**50,264,725**	**50,017,259**	**52,312,426**	**54,819,517**	**56,766,481**	**60,112,863**	**66,497,549**	**68,512,419**	**72,728,369**	**100.0%**

VISAYAS	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	% Share
Coal	**313,542**	**587,626**	**646,077**	**603,903**	**718,663**	**848,428**	**745,686**	**822,007**	**1,528,682**	**4,032,202**	**4,701,053**	**4,689,683**	**4,449,483**	**4,968,437**	**5,270,242**	**6,623,593**	**6,784,714**	**47.6%**
Oil-based	**1,651,665**	**1,860,563**	**1,997,708**	**1,799,876**	**1,281,766**	**1,477,089**	**1,664,802**	**1,863,970**	**1,726,580**	**683,226**	**734,172**	**796,470**	**765,893**	**672,207**	**637,405**	**541,022**	**352,598**	**2.5%**
Diesel	*1,378,402*	*1,480,745*	*1,649,383*	*1,486,431*	*1,165,700*	*1,334,868*	*1,432,627*	*1,554,155*	*1,446,180*	*448,577*	*514,274*	*528,780*	*614,558*	*672,207*	637,405	541,022	352,598	*2.5%*
Gas Turbine	*7,499*	*40,236*	*82,094*	*23,862*	*193*	*9,045*	*36,485*	*61,972*	*3,164*	*0*	*0*	*0*	*0*	*0*	0	0	0	*0.0%*
Oil Thermal	*265,763*	*339,582*	*266,231*	*289,582*	*115,873*	*133,176*	*195,690*	*247,843*	*277,236*	*234,649*	*219,899*	*267,689*	*151,335*	*0*	0	0	0	*0.0%*
Natural Gas	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**7,815**	**4,269**	**0**	**0**	**0**	**0**	**0.0%**
Renewable Energy (RE)	**4,133,607**	**6,393,997**	**6,372,594**	**6,294,573**	**6,128,295**	**5,776,075**	**6,239,206**	**6,038,321**	**5,820,003**	**5,740,314**	**6,047,489**	**5,605,626**	**5,794,279**	**6,529,839**	**7,047,239**	**6,889,270**	**7,129,177**	**50.0%**
Geothermal	*4,108,410*	*6,360,964*	*6,338,317*	*6,267,377*	*6,100,202*	*5,746,878*	*6,199,159*	*5,984,957*	*5,771,218*	*5,615,561*	*5,930,484*	*5,463,017*	*5,627,241*	*6,105,383*	5,974,487	5,563,581	5,737,443	*40.2%*
Hydro	*25,197*	*33,033*	*34,277*	*27,196*	*28,093*	*29,197*	*40,047*	*42,406*	*35,889*	*53,117*	*46,161*	*36,936*	*35,475*	*38,375*	63,532	90,087	72,562	*0.5%*
Biomass	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*10,957*	*12,896*	*71,636*	*70,844*	*105,673*	*116,523*	*158,864*	276,053	414,483	439,269	*3.1%*
Solar	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*15,040*	*70,559*	524,658	626,957	658,244	*4.6%*
Wind	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*156,658*	208,509	194,161	221,660	*1.6%*
Total Generation	**6,098,814**	**8,842,186**	**9,016,379**	**8,698,352**	**8,128,723**	**8,101,593**	**8,649,694**	**8,724,298**	**9,075,264**	**10,455,743**	**11,482,714**	**11,099,593**	**11,013,924**	**12,170,483**	**12,954,886**	**14,053,885**	**14,266,489**	**100.0%**

MINDANAO	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	% Share
Coal	**0**	**0**	**0**	**0**	**476,245**	**1,570,872**	**1,499,380**	**1,562,753**	**1,725,839**	**1,628,848**	**1,686,314**	**1,635,380**	**1,257,542**	**2,037,738**	**4,889,542**	**6,271,010**	**7,785,345**	**61.0%**
Oil-based	**1,016,537**	**1,713,693**	**1,915,799**	**2,319,927**	**1,671,619**	**1,478,868**	**1,275,288**	**1,652,415**	**2,087,250**	**1,423,688**	**1,719,521**	**2,093,504**	**2,599,495**	**3,369,442**	**2,462,172**	**866,879**	**632,525**	**5.0%**
Diesel	*1,016,082*	*1,711,563*	*1,915,500*	*2,319,772*	*1,671,376*	*1,478,775*	*1,275,010*	*1,622,575*	*2,082,124*	*1,423,433*	*1,718,684*	*2,092,831*	*2,595,139*	*3,365,393*	2,462,172	866,879	632,525	*5.0%*
Oil Thermal	*455*	*2,129*	*299*	*155*	*242*	*93*	*278*	*29,840*	*5,126*	*256*	*837*	*673*	*4,356*	*4,050*	0	0	0	*0.0%*
Natural Gas	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0.0%**
Renewable Energy (RE)	**4,965,201**	**4,850,029**	**5,171,340**	**4,922,732**	**5,266,085**	**4,840,544**	**5,197,088**	**5,020,111**	**4,589,680**	**5,650,112**	**5,721,036**	**5,617,847**	**5,623,555**	**4,722,686**	**3,993,743**	**4,666,147**	**4,351,990**	**34.1%**
Geothermal	*857,912*	*861,015*	*909,815*	*892,863*	*845,660*	*867,308*	*793,700*	*822,926*	*834,439*	*840,956*	*731,089*	*742,980*	*863,542*	*841,857*	869,002	796,792	826,378	*6.5%*
Hydro	*4,107,289*	*3,989,013*	*4,261,525*	*4,028,352*	*4,419,049*	*3,971,927*	*4,402,084*	*4,195,934*	*3,753,987*	*4,807,945*	*4,913,491*	*4,826,851*	*4,744,638*	*3,857,878*	3,036,282	3,791,144	3,366,284	*26.4%*
Biomass	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*75,136*	*46,602*	*13,897*	*21,403*	11,046	0	71,586	*0.6%*
Solar	*0*	*0*	*0*	*1,517*	*1,376*	*1,309*	*1,304*	*1,252*	*1,254*	*1,212*	*1,320*	*1,414*	*1,477*	*1,548*	77,412	78,211	87,742	*0.7%*
Wind	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	0	0	0	*0.0%*
Total Generation	**5,981,738**	**6,563,721**	**7,087,140**	**7,242,659**	**7,413,949**	**7,890,283**	**7,971,756**	**8,235,278**	**8,402,769**	**8,702,648**	**9,126,871**	**9,346,731**	**9,480,592**	**10,129,866**	**11,345,457**	**11,804,037**	**12,769,861**	**100.0%**

PHILIPPINES by Grid	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	% Share
Luzon	36,386,885	37,534,630	39,853,911	40,626,730	41,241,457	43,619,911	44,199,534	44,974,855	50,264,725	50,017,259	52,312,426	54,819,517	56,766,481	60,112,863	66,497,549	68,512,419	72,728,369	72.9%
Visayas	6,098,814	8,842,186	9,016,379	8,698,352	8,128,723	8,101,593	8,649,694	8,724,298	9,075,264	10,455,743	11,482,714	11,099,593	11,013,924	12,170,483	12,954,886	14,053,885	14,266,489	14.3%
Mindanao	5,981,738	6,563,721	7,087,140	7,242,659	7,413,949	7,890,283	7,971,756	8,235,278	8,402,769	8,702,648	9,126,871	9,346,731	9,480,592	10,129,866	11,345,457	11,804,037	12,769,861	12.8%
Total Generation	**48,467,436**	**52,940,537**	**55,957,430**	**56,567,740**	**56,784,130**	**59,611,788**	**60,820,985**	**61,934,432**	**67,742,759**	**69,175,650**	**72,922,011**	**75,265,842**	**77,260,997**	**82,413,213**	**90,797,891**	**94,370,341**	**99,764,718**	**100.0%**

DEPARTMENT OF ENERGY

2018 POWER STATISTICS

Gross Power Generation by Plant Type*
in MWh

PHILIPPINES by Plant Type	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	% Share
Coal	**16,127,886**	**14,938,748**	**16,194,412**	**15,257,178**	**15,294,066**	**16,837,096**	**15,748,794**	**16,476,136**	**23,301,105**	**25,342,176**	**28,264,867**	**32,081,007**	**33,053,518**	**36,685,685**	**43,303,242**	**46,847,274**	**51,932,187**	**52.1%**
Oil-based	**6,293,233**	**7,170,115**	**8,504,321**	**6,141,444**	**4,664,799**	**5,148,006**	**4,868,333**	**5,380,666**	**7,101,002**	**3,397,599**	**4,254,015**	**4,490,600**	**5,707,748**	**5,886,437**	**5,661,408**	**3,787,093**	**3,172,817**	**3.2%**
Combined Cycle	*748,450*	*438,755*	*738,437*	*90,608*	*238,870*	*652,834*	*513,442*	*638,520*	*1,202,040*	*123,556*	*227,354*	*247,159*	*514,980*	*275,892*	*693,685*	*405,022*	*522,115*	0.5%
Diesel	*4,560,984*	*5,509,409*	*6,253,077*	*5,716,977*	*4,152,144*	*4,161,675*	*3,660,388*	*3,771,289*	*4,531,688*	*2,762,331*	*3,332,081*	*3,805,078*	*4,730,219*	*5,520,716*	*4,722,326*	*3,100,113*	*2,505,300*	2.5%
Gas Turbine	*36,838*	*41,972*	*82,277*	*25,295*	*193*	*9,045*	*36,485*	*61,972*	*3,164*	*0*	*0*	*0*	*0*	*10,290*	*499*	*0*	*0*	0.0%
Oil Thermal	*946,961*	*1,179,979*	*1,430,529*	*308,564*	*273,593*	*324,452*	*658,018*	*908,885*	*1,364,111*	*511,712*	*694,580*	*438,363*	*462,550*	*79,539*	*244,898*	*281,958*	*145,402*	0.1%
Natural Gas	**8,770,851**	**13,139,410**	**12,384,467**	**16,860,917**	**16,365,960**	**18,789,414**	**19,575,855**	**19,886,827**	**19,517,854**	**20,591,323**	**19,641,527**	**18,791,286**	**18,690,077**	**18,877,915**	**19,853,783**	**20,547,239**	**21,333,789**	**21.4%**
Renewable Energy (RE)	**17,275,466**	**17,692,264**	**18,874,230**	**18,308,202**	**20,459,304**	**18,837,272**	**20,628,003**	**20,190,804**	**17,822,798**	**19,844,551**	**20,761,602**	**19,902,949**	**19,809,655**	**20,963,175**	**21,979,459**	**23,188,735**	**23,325,925**	**23.4%**
Geothermal	10,242,493	9,822,444	10,281,550	9,902,443	10,465,279	10,214,688	10,722,780	10,323,847	9,929,152	9,942,330	10,249,990	9,604,598	10,308,113	11,043,694	11,070,403	10,270,077	10,435,305	10.5%
Hydro	7,032,973	7,869,820	8,592,681	8,386,773	9,939,413	8,563,433	9,842,534	9,787,567	7,803,405	9,697,532	10,252,134	10,019,308	9,137,273	8,665,078	8,110,915	9,610,799	9,383,758	9.4%
Biomass	0	0	0	0	0	0	0	13,710	27,270	115,274	182,819	211,973	195,699	367,456	725,906	1,013,148	1,104,823	1.1%
Solar	0	0	0	1,517	1,376	1,309	1,304	1,252	1,254	1,212	1,320	1,414	16,517	138,534	1,097,016	1,201,152	1,249,116	1.3%
Wind	0	0	0	17,469	53,235	57,842	61,386	64,428	61,717	88,204	75,339	65,655	152,052	748,414	975,219	1,093,558	1,152,923	1.2%
Total Generation	**48,467,436**	**52,940,537**	**55,957,430**	**56,567,740**	**56,784,130**	**59,611,788**	**60,820,985**	**61,934,432**	**67,742,759**	**69,175,650**	**72,922,011**	**75,265,842**	**77,260,997**	**82,413,213**	**90,797,891**	**94,370,341**	**99,764,718**	**100.0%**

Note:
Generation data includes grid connected, embedded and off-grid generator.
Revised as of 29 March 2019

DEPARTMENT OF ENERGY

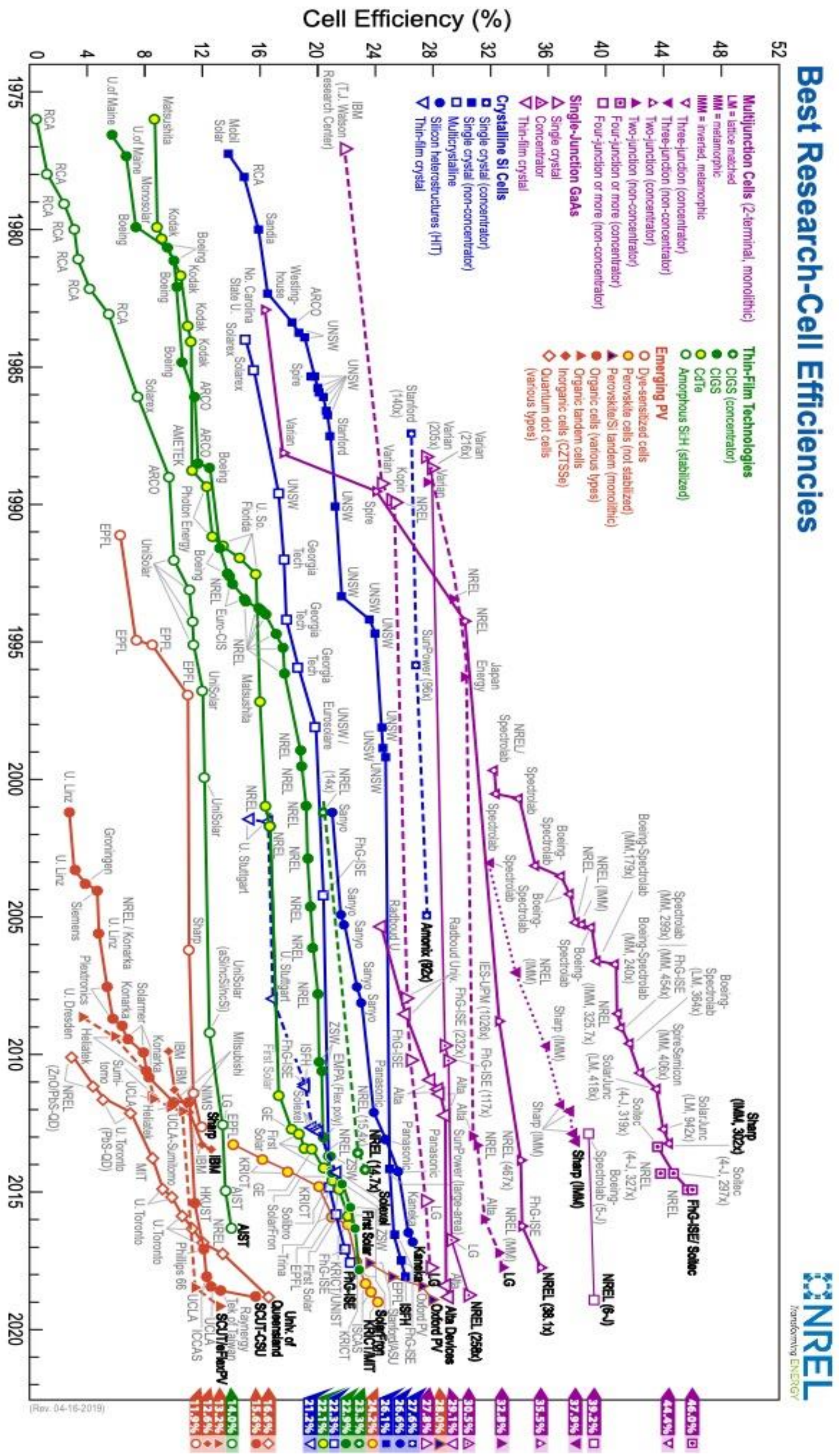
2018 POWER STATISTICS

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Power Consumption by Sector In GWh																
Residential	15,357	15,920	16,031	15,830	16,376	16,644	17,504	18,833	18,694	19,695	20,614	20,969	22,747	25,631	26,782	28,261
Commercial	11,106	11,785	12,245	12,679	13,470	14,136	14,756	16,261	16,624	17,777	18,304	18,761	20,085	21,770	22,768	24,016
Industrial	15,188	15,012	15,705	15,888	16,522	17,031	17,084	18,576	19,334	20,071	20,677	21,429	22,514	24,117	25,573	27,587
Others	1,069	1,359	1,177	1,275	1,641	1,395	1,523	1,596	1,446	1,668	1,971	2,186	2,462	2,634	2,670	2,753
Electricity Sales	42,720	44,076	45,159	45,672	48,009	49,206	50,868	55,266	56,098	59,211	61,566	63,345	67,808	74,153	77,793	82,617
Utilities Own Use	3,410	4,654	4,591	4,227	3,994	3,935	3,524	4,677	5,398	5,351	5,959	6,461	7,124	8,357	8,316	8,141
Power Losses	6,810	7,228	6,817	6,885	7,608	7,680	7,542	7,800	7,680	8,360	7,741	7,455	7,481	8,288	8,262	9,007
Total	52,941	55,957	56,568	56,784	59,612	60,821	61,934	67,743	69,176	72,922	75,266	77,261	82,413	90,798	94,370	99,765
Power Generation by Grid In GWh																
Luzon	37,535	39,854	40,627	41,241	43,620	44,200	44,975	50,265	50,017	52,312	54,820	56,766	60,113	66,498	68,512	72,728
Visayas	8,842	9,016	8,698	8,129	8,102	8,650	8,724	9,075	10,456	11,483	11,100	11,014	12,170	12,955	14,054	14,266
Mindanao	6,564	7,087	7,243	7,414	7,890	7,972	8,235	8,403	8,703	9,127	9,347	9,481	10,130	11,345	11,804	12,770
Total	52,941	55,957	56,568	56,784	59,612	60,821	61,934	67,743	69,176	72,922	75,266	77,261	82,413	90,798	94,370	99,765
Power Generation by Source In GWh, Total Philippines																
Coal	14,939	16,194	15,257	15,294	16,837	15,749	16,476	23,301	25,342	28,265	32,081	33,054	36,686	43,303	46,847	51,932
Oil-Based	7,170	8,504	6,141	4,665	5,148	4,868	5,381	7,101	3,398	4,254	4,491	5,708	5,886	5,661	3,787	3,173
Combined Cycle	*439*	*738*	*91*	*239*	*653*	*513*	*639*	*1,202*	*124*	*227*	*247*	*515*	*276*	*694*	*405*	*522*
Diesel	*5,509*	*6,253*	*5,717*	*4,152*	*4,162*	*3,660*	*3,771*	*4,532*	*2,762*	*3,332*	*3,805*	*4,730*	*5,521*	*4,722*	*3,100*	*2,505*
Gas Turbine	*42*	*82*	*25*	*0*	*9*	*36*	*62*	*3*	*0*	*0*	*0*	*0*	*10*	*0*	*0*	*0*
Oil Thermal	*1,180*	*1,431*	*309*	*274*	*324*	*658*	*909*	*1,364*	*512*	*695*	*438*	*463*	*80*	*245*	*282*	*145*
Natural Gas	13,139	12,384	16,861	16,366	18,789	19,576	19,887	19,518	20,591	19,642	18,791	18,690	18,878	19,854	20,547	21,334
Renewable Energy (RE)	17,692	18,874	18,308	20,459	18,837	20,628	20,191	17,823	19,845	20,762	19,903	19,810	20,963	21,979	23,189	23,326
Geothermal	*9,822*	*10,282*	*9,902*	*10,465*	*10,215*	*10,723*	*10,324*	*9,929*	*9,942*	*10,250*	*9,605*	*10,308*	*11,044*	*11,070*	*10,270*	*10,435*
Hydro	*7,870*	*8,593*	*8,387*	*9,939*	*8,563*	*9,843*	*9,788*	*7,803*	*9,698*	*10,252*	*10,019*	*9,137*	*8,665*	*8,111*	*9,611*	*9,384*
Biomass	*0*	*0*	*0*	*0*	*0*	*0*	*14*	*27*	*115*	*183*	*212*	*196*	*367*	*726*	*1,013*	*1,105*
Solar	*0*	*0*	*2*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*17*	*139*	*1,097*	*1,201*	*1,249*
Wind	*0*	*0*	*17*	*53*	*58*	*61*	*64*	*62*	*88*	*75*	*66*	*152*	*748*	*975*	*1,094*	*1,153*
Total	52,941	55,957	56,568	56,784	59,612	60,821	61,934	67,743	69,176	72,922	75,266	77,261	82,413	90,798	94,370	99,765
Installed Generating Capacity In MW																
Coal	3,958	3,967	3,967	4,177	4,213	4,213	4,277	4,867	4,917	5,568	5,568	5,708	5,963	7,419	8,049	8,844
Oil Based	3,604	3,669	3,663	3,602	3,616	3,353	3,193	3,193	2,994	3,074	3,353	3,476	3,610	3,616	4,153	4,292
Natural Gas	2,763	2,763	2,763	2,763	2,834	2,831	2,831	2,861	2,861	2,862	2,862	2,862	2,862	3,431	3,447	3,453
Renewable Energy (RE)	4,799	5,149	5,226	5,261	5,277	5,284	5,309	5,437	5,391	5,521	5,541	5,898	6,330	6,958	7,079	7,227
Geothermal	*1,932*	*1,932*	*1,978*	*1,978*	*1,958*	*1,958*	*1,953*	*1,966*	*1,783*	*1,848*	*1,868*	*1,918*	*1,917*	*1,916*	*1,916*	*1,944*
Hydro	*2,867*	*3,217*	*3,222*	*3,257*	*3,293*	*3,291*	*3,291*	*3,400*	*3,491*	*3,521*	*3,521*	*3,543*	*3,600*	*3,618*	*3,627*	*3,701*
Biomass	*0*	*0*	*0*	*0*	*0*	*0*	*30*	*38*	*83*	*119*	*119*	*131*	*221*	*233*	*224*	*258*
Solar	*0*	*0*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*23*	*165*	*765*	*885*	*896*
Wind	*0*	*0*	*25*	*25*	*25*	*33*	*33*	*33*	*33*	*33*	*33*	*283*	*427*	*427*	*427*	*427*
Total	15,124	15,548	15,619	15,803	15,941	15,681	15,610	16,358	16,162	17,025	17,325	17,944	18,765	21,423	22,728	23,815
Dependable Generating Capacity In MW																
Coal	3,691	3,696	3,432	3,638	3,467	3,412	3,813	4,245	4,651	5,206	5,206	5,378	5,613	6,979	7,674	8,368
Oil Based	3,175	3,216	3,043	2,879	2,670	2,702	2,528	2,488	2,579	2,561	2,846	2,705	2,734	2,821	3,286	2,995
Natural Gas	2,703	2,703	2,703	2,703	2,703	2,562	2,700	2,756	2,770	2,760	2,760	2,760	2,759	3,291	3,291	3,286
Renewable Energy (RE)	3,835	4,178	4,417	4,419	4,639	4,372	4,278	4,413	4,477	4,539	4,559	4,789	5,325	6,005	6,264	6,592
Geothermal	*1,568*	*1,568*	*1,683*	*1,683*	*1,667*	*1,388*	*1,321*	*1,351*	*1,434*	*1,462*	*1,482*	*1,607*	*1,601*	*1,689*	*1,752*	*1,770*
Hydro	*2,267*	*2,610*	*2,723*	*2,726*	*2,962*	*2,950*	*2,914*	*3,021*	*2,963*	*2,983*	*2,983*	*2,982*	*3,073*	*3,181*	*3,269*	*3,473*
Biomass	*0*	*0*	*0*	*0*	*0*	*0*	*10*	*20*	*46*	*76*	*76*	*81*	*146*	*157*	*160*	*182*
Solar	*0*	*0*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*0*	*0*	*17*	*125*	*594*	*700*	*740*
Wind	*0*	*0*	*9*	*9*	*9*	*33*	*33*	*20*	*33*	*17*	*17*	*103*	*379*	*383*	*383*	*427*
Total	13,404	13,792	13,595	13,639	13,479	13,049	13,319	13,902	14,477	15,066	15,371	15,633	16,432	19,097	20,515	21,241

Note: *IPPs generation included in the utility
Generation data includes grid connected, embedded and off-grid generator.
2018 capacity mix includes off-grd capacities
Revised as of 29 March 2019

Appendix B

Best research PV cell efficiencies



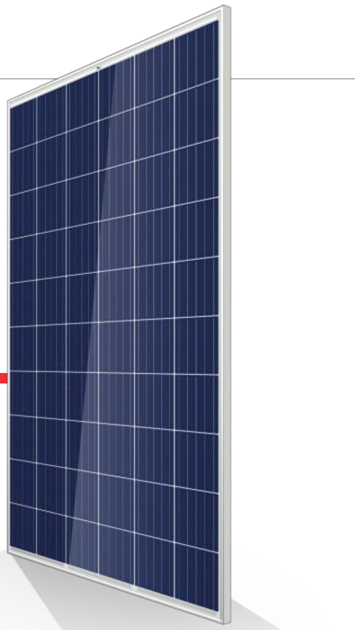
Appendix C

Trinasolar PV module specifications

Mono Multi Solutions

Honey MODULE

TSM-PD05



60 CELL
MULTICRYSTALLINE MODULE

270–285W
POWER OUTPUT RANGE

17.4%
MAXIMUM EFFICIENCY

0/+5W
POSITIVE POWER TOLERANCE

Founded in 1997, Trina Solar is the world's leading comprehensive solutions provider for solar energy. We believe close cooperation with our partners is critical to success. Trina Solar now distributes its PV products to over 60 countries all over the world. Trina Solar is able to provide exceptional service to each customer in each market and supplement our innovative, reliable products with the backing of Trina Solar as a strong, bankable partner. We are committed to building strategic, mutually benef cial collaboration with installers, developers, distributors and other partners.

Comprehensive Product And System Certificates

IEC61215/IEC61730/UL1703/IEC61701/IEC62716
ISO9001: Quality Management System
ISO14001: Environmental Management System
ISO14064: Greenhouse Gas Emissions Verif cation
OHSAS18001: Occupational Health and Safety Management System

Trinasolar

Excellent low light performance on cloudy days, mornings and evenings

- Advanced surface texturing
- Back surface f eld
- Selective emitter

Maximize Limited Space

- 60-cell module power output up to 285W
- Up to 174 W/m2 power density

Highly reliable due to stringent quality control

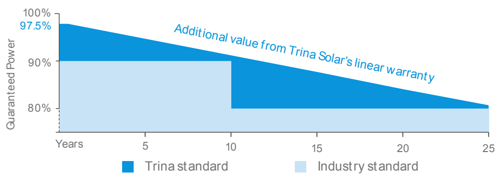
- All modules have to pass electroluminescence (EL) inspection
- Over 30 in-house tests (UV, TC, HF, and many more)
- In-house testing goes well beyond certif cation requirements
- PID resistant
- 1000 V UL/1000 V IEC certif ed

Certif ed to withstand challenging environmental conditions

- 130 km/h wind load (2400 Pa)
- 900 kg snow load per module (5400 Pa)
- 35 mm hail stones at 97 km/h
- Ammonia resistance
- Salt mist resistance
- Resistance to sand and dust abrasion

LINEAR PERFORMANCE WARRANTY

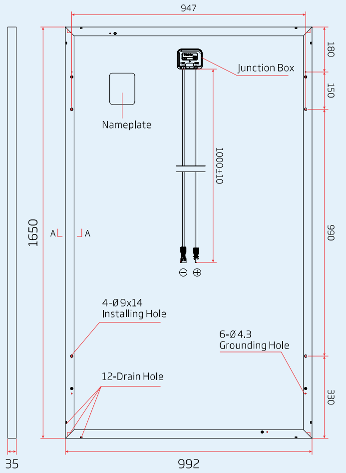
10 Year Product Warranty · 25 Year Linear Power Warranty



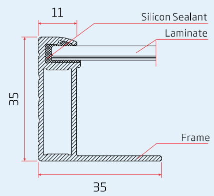
Honey

TSM-PD05

DIMENSIONS OF PV MODULE TSM-PD05 (unit: mm)

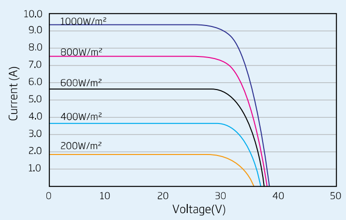


Back View

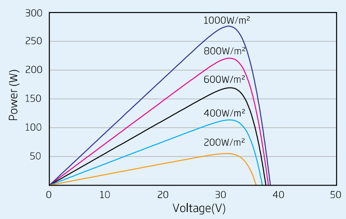


(A-A)

I-V CURVES OF PV MODULE (280W)



P-V CURVES OF PV MODULE (280W)



ELECTRICAL DATA @ STC	TSM-270 PD05	TSM-275 PD05	TSM-280 PD05	TSM-285 PD05
Peak Power Watts-P_{MAX} (Wp)*	270	275	280	285
Power Output Tolerance-P_{MAX} (W)	0/+5	0/+5	0/+5	0/+5
Maximum Power Voltage-V_{MPP} (V)	30.9	31.1	31.4	31.6
Maximum Power Current-I_{MPP} (A)	8.73	8.84	8.92	9.02
Open Circuit Voltage-V_{OC} (V)	37.9	38.1	38.2	38.3
Short Circuit Current-I_{SC} (A)	9.22	9.32	9.40	9.49
Module Efficiency η_m (%)	16.5	16.8	17.1	17.4

STC: Irradiance 1000 W/m², Cell Temperature 25°C, Air Mass AM1.5
* Measuring tolerance: ±3%

ELECTRICAL DATA @ NOCT	TSM-270 PD05	TSM-275 PD05	TSM-280 PD05	TSM-285 PD05
Maximum Power-P_{MAX} (Wp)	200	204	208	211
Maximum Power Voltage-U_{MPP} (V)	28.6	28.8	29.0	29.2
Maximum Power Current-I_{MPP} (A)	7.00	7.09	7.15	7.23
Open Circuit Voltage-U_{OC} (V)	35.1	35.3	35.4	35.5
Short Circuit Current-I_{SC} (A)	7.44	7.52	7.59	7.66

NOCT: Irradiance at 800 W/m², Ambient Temperature 20°C, Wind Speed 1 m/s.

MECHANICAL DATA

Solar Cells	Multicrystalline 156.75 × 156.75 mm
Cell Orientation	60 cells (6 x 10)
Module Dimensions	1650 × 992 × 35 mm
Weight	18.6 kg
Glass	3.2 mm, high transparency, AR coated and heat tempered solar glass
Backsheet	White
Frame	Silver Anodized Aluminium Alloy
J-Box	IP 67 or IP 68 rated
Cables	Photovoltaic Technology Cable 4.0mm², 1000 mm
Connector	EU Countries: 28 MC4 / UTX / TS4, Non-EU Countries: 28 QC4 / TS4

TEMPERATURE RATINGS

Nominal Operating Cell Temperature (NOCT)	44°C (±2K)
Temperature Coefficient of P_{MAX}	- 0.41%/K
Temperature Coefficient of V_{OC}	- 0.32%/K
Temperature Coefficient of I_{SC}	0.05%/K

MAXIMUM RATINGS

Operational Temperature	-40 to +85°C
Maximum System Voltage	1000V DC (IEC) 1000V DC (UL)
Max Series Fuse Rating*	15 A
Mechanical Load	5400 Pa
Wind Load	2400 Pa

* DO NOT connect fuse in combiner box with two or more strings in parallel connection

WARRANTY

10 year Product Workmanship Warranty

25 year Linear Performance Warranty

(Please refer to product warranty for details)

PACKAGING CONFIGURATION

Modules per box:	30 pieces
Modules per 40' container:	840 pieces

TSM_EN_2017_B

Trinasolar

CAUTION: READ SAFETY AND INSTALLATION INSTRUCTIONS BEFORE USING THE PRODUCT.

www.trinasolar.com

Appendix D

TESLA powerpack specifications

POWERPACK

TESLA COMMERCIAL BATTERY

Tesla has been building integrated battery systems in cars for over 10 years. The same degree of expertise, quality control and technological innovation has informed our process of developing high-performance energy storage systems. Powerpack offers commercial and utility customers a turn-key energy storage solution to maximize on-site clean power and energy savings. The Powerpack system scales to the space, power and energy requirements of any site from 100 kWh to 100 MWh+.

Powerpack System Includes a Bi-Directional Inverter and DC Battery Packs

FULLY INTEGRATED SYSTEM

A complete energy storage system including DC batteries, bi-directional inverter, and a Powerpack controller with intelligent software. This turnkey system is designed to maximize savings and prolong battery life.

OPTIMIZATION SOFTWARE

Powerpack systems have the most advanced battery technology and dispatch optimization software to quickly learn and predict a facility's energy patterns. Tesla's proprietary storage dispatch software can charge and discharge autonomously to maximize customer value.

ENHANCED SYSTEM SAFETY

Powerpack's battery architecture consists of a low voltage battery with a DC/DC converter for added electrical isolation and safety. It also has an integrated liquid cooling / heating system for thermal safety and enhanced performance and reliability.

APPLICATIONS

PEAK SHAVING
Discharge at times of peak demand to reduce expensive demand charges

EMERGENCY BACKUP
Powers a facility when the grid goes down

CAPACITY FIRMING
Smooth out the intermittency of renewables by storing and dispatching when needed

LOAD SHIFTING
Shift energy consumption from one point in time to another

MICROGRID
Build a localized grid that can disconnect from the main power grid

TRANSMISSION & DISTRIBUTION SUPPORT
Supply power at a distributed location to defer the need to upgrade aging infrastructure

DEMAND RESPONSE
Discharge or charge in response to signals from a demand response administrator

ANCILLARY SERVICES
Provide service to the grid in response to signals sent

TESLA

MORE DETAILS: WWW.TESLA.COM/ENERGY

POWERPACK DETAILS:

1 Powerpack includes 16 individual battery pods

Each pod has an isolated DC/DC inverter and thermal control system

Sensors to monitor cell-level performance in real-time

POWERPACK SPECIFICATIONS

MECHANICAL AND MOUNTING

Enclosure	IP67 (Pod) NEMA 34 / IP35 (Powerpack) NEMA 3R / IP54 (Inverter)
Powerpack Weight	1720 kg / 3800 lbs
Powerpack Dimensions	L: 52" (1321mm) W: 38" (966mm) H: 86" (2185mm)
Powerpack Area Requirements	50kW / 95kWh: 8.9m ^{2} 100kW / 190kWh: 11.8m ^{2} 250kW / 475kWh: 20.5m ^{2} 500kW / 950kWh: 35m ^{2}
Inverter Dimensions	L: 39.9" (1014mm) W: 49.4" (1254mm) H: 86.3" (2192mm)
Operating Ambient Temperature	-13°F to 122°F / -30°C to 50°C
Installation	Requires a crane Unit ships on removable 130mm tall pallet

COMMUNICATIONS

Protocol	Modbus TCP DNP3 Rest API

SYSTEM SPECIFICATIONS

ELECTRICAL

AC Voltage	480VAC 3-phase 400VAC 3-phase
System Availability	50 Hz, 60 Hz
System Sizes	Scalable from 50kW - 500kW
Continuous Power Duration	2 hours
System Efficiency @C/2	87% Roundtrip*

*Net energy delivered at 25 °C (77 °F) ambient temperature including thermal control.

REGULATORY

Lithium-Ion Cells	NRTL listed to UL 1642
System	NRTL listed to UL 1973, 9540, 1741 IEEE 1547 Compliant to grid codes and safety standards of all major markets. The full list can be provided upon request.

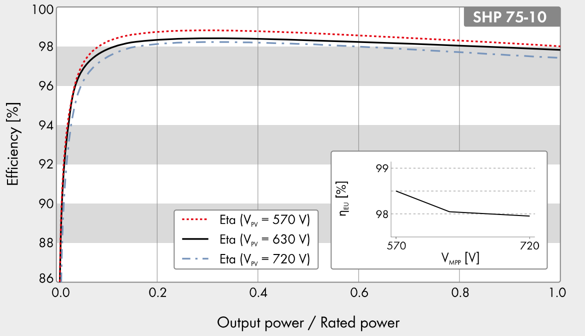
TESLA

MORE DETAILS: WWW.TESLA.COM/ENERGY

Appendix E

PV Sol inverter specifications

Efficiency curve

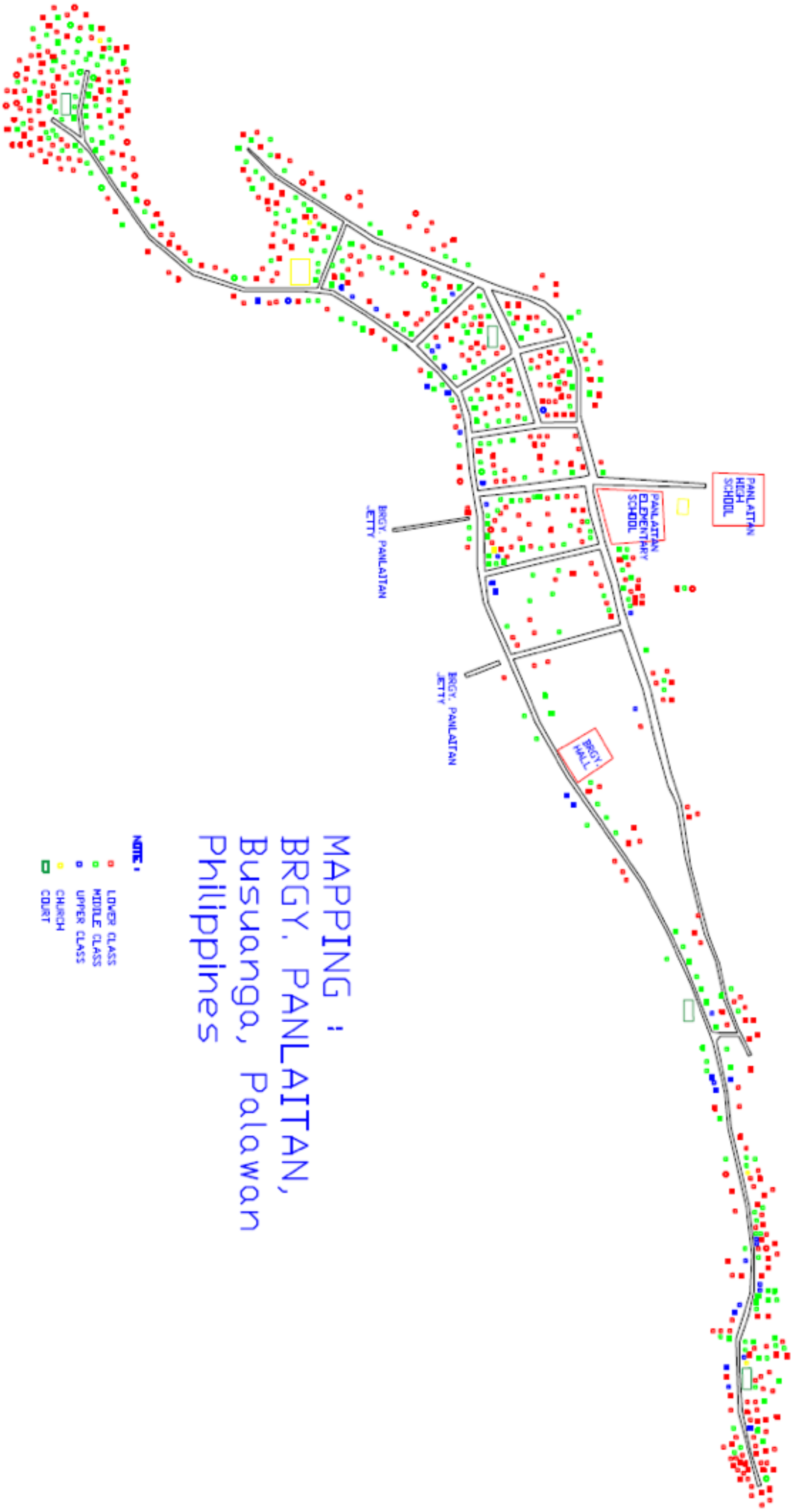


● Standard features ○ Optional – Not available
Data at nominal conditions
Last revision: October 2017

Technical Data	Sunny Highpower PEAK1
Input (DC)	
Max. generator power	112500 Wp
Rated power (DC)	76500 W
Max. input voltage	1000 V
MPP voltage range (at 400 Vac / 480 Vac)	570 V to 800 V / 685 V to 800 V
Min. input voltage (at 400 Vac / 480 Vac)	565 V / 680 V
Start input voltage (at 400 Vac / 480 Vac)	600 V / 720 V
Max. input current / max. short circuit current	140 A / 210 A
Number of independent MPP inputs / strings per MPP input	1 / 1 (split up in external combiner box)
Rated DC input voltage (at 400 Vac / 480 Vac)	630 V / 710 V
Output (AC)	
Rated power at nominal voltage	75000 W
Max. apparent AC power	75000 VA
Max. reactive power	75000 var
Nominal AC voltage	3 / PE, 400 V to 480 V, ±10 %
AC voltage range	360 V to 530 V
AC power frequency/range	50 Hz / 44 Hz to 55 Hz 60 Hz / 54 Hz to 65 Hz
Rated power frequency/rated grid voltage	50 Hz / 400 V
Max. output current (at 400 Vac)	109 A
Power factor at rated power / displacement power factor adjustable	1 / 0 overexcited to 0 underexcited
THD	≤ 1 %
Feed-in phases/connection phases	3 / 3
Efficiency	
Max. efficiency / Euro-eta	98.8% / 98.2%
Protective devices	
Input-side disconnection point	●
Ground fault monitoring/grid monitoring	● / ●
Integrated DC surge arrester / AC surge arrester	Type II / type II + III (combined)
AC short-circuit current capability / galvanically isolated	● / –
All-pole sensitive residual-current monitoring unit	●
Protection class (as per IEC 62109-1) / overvoltage category (as per IEC 62109-1)	I / AC: III; DC: II
General data	
Dimensions (W/H/D)	570 / 740 / 306 mm (22.4 / 29.1 / 12.0 inches)
Weight	77 kg (170 lb)
Operating temperature range	−25°C to +60°C (−13°F to +140°F)
Noise emission, typical	58 dB(A)
Self-consumption (at night)	< 3 W
Topology / cooling concept	Transformerless / active
Degree of protection (according to IEC 60529 / UL 50E)	IP65 / NEMA 3R
Climatic category (as per IEC 60721-3-4)	4K4H/4Z4/4B2/4S3/4M2/4C2
Max. permissible value for relative humidity (non-condensing)	95 %
Features / function / accessories	
DC connection / AC connection	Screw terminal / screw terminal
Display	Graphical
Data interface	SunSpec Modbus TCP (via external SMA Inverter Manager)
Off-grid capable / PV-diesel capable	– / ●
Warranty: 5/10/15/20 years	● / ○ / ○ / ○
Planned Certificates and approvals * Does not apply to all national appendixes of EN 50438 ** Restricted (Note Manufacturer's Declaration)	AS 4777, BDEW 2008, C10/11:2012**, CEI 0-16, DEWA 2015, EN 50438*, G59/3, IEC 60068-2-x, IEC 61727, IEC 62109-1/2, IEC 62116, LEY N° 20751, NEN EN 50438, NRS 097-2-1, PEA 2015, R.D.661/2007, Res. n°7:2013, SI4777, TORD4**, UTE C15-712-1, VDE 0126-1-1, VDE-AR-N 4105**, VFR 2014
Type designation	SHP 75-10

Appendix F

Sitemap of Panlaitan for load point assessment



Appendix G

Load classification and profiling for Panlaitan

	Overall Load Profile																		
Classification	Res Type 01		Res Type 02		Res Type 03		Residential	Store		Church		Bgy Hall		School		Basketball Court		Comm & Public Buildings	total
Amount	441		298		38			19		6		1		2		4			
Load factor	0.8		0.8		0.8			0.8		1		1		1		1			
Quantity	352.8		238.4		30.4			15.2		6		1		2		4			
P max (each) [kW]	3.4		5.9		6.6			19.8		3.5		8.2		14.9		1.2			196.785
	kW	kWh	kW	kWh	kW	kWh		kW	kWh	kW	kWh	kW	kWh	kW	kWh	kW	kWh		kWh
	3.4	1208.3	5.9	1402.4	6.6	199.8		19.8	301.0	3.5	20.9	8.2	8.2		29.7	1.2	4.8		3175.097
0	0.03	10.58	0.15	34.57	0.16	4.71	49.86	0.18	2.74	0.00	0.00	0.03	0.03	0.06	0.12	0.00	0.00	2.89	52.75
1	0.03	10.58	0.15	34.57	0.16	4.71	49.86	0.18	2.74	0.00	0.00	0.03	0.03	0.06	0.12	0.00	0.00	2.89	52.75
2	0.03	10.58	0.15	34.57	0.16	4.71	49.86	0.18	2.74	0.00	0.00	0.03	0.03	0.06	0.12	0.00	0.00	2.89	52.75
3	0.03	10.58	0.15	34.57	0.16	4.71	49.86	0.18	2.74	0.00	0.00	0.03	0.03	0.06	0.12	0.00	0.00	2.89	52.75
4	0.03	10.58	0.15	34.57	0.16	4.71	49.86	0.18	2.74	0.00	0.00	0.03	0.03	0.06	0.12	0.00	0.00	2.89	52.75
5	0.03	10.58	0.15	34.57	0.18	5.32	50.47	0.54	8.21	0.00	0.00	0.03	0.03	0.06	0.12	0.00	0.00	8.36	58.83
6	0.09	31.75	0.22	51.26	0.25	7.45	90.46	0.54	8.21	0.36	2.16	0.21	0.21	1.29	2.58	0.00	0.00	13.16	103.61
7	0.14	49.39	0.31	72.71	0.34	10.18	132.29	0.85	12.95	0.36	2.16	0.21	0.21	1.26	2.52	0.00	0.00	17.84	150.13
8	0.20	70.56	0.36	85.82	0.40	12.16	168.54	0.95	14.47	0.36	2.16	0.71	0.71	1.36	2.72	0.00	0.00	20.06	188.60
9	0.16	56.45	0.34	79.86	0.44	13.22	149.54	1.29	19.64	0.36	2.16	0.71	0.71	1.46	2.92	0.00	0.00	25.43	174.96
10	0.17	59.98	0.21	50.66	0.30	9.20	119.83	1.27	19.27	0.34	2.04	0.68	0.68	1.46	2.92	0.00	0.00	24.91	144.74
11	0.21	74.09	0.35	84.04	0.38	11.63	169.75	1.24	18.91	0.34	2.04	0.68	0.68	0.76	1.52	0.00	0.00	23.14	192.90
12	0.27	93.49	0.30	72.12	0.33	10.11	175.72	1.14	17.39	0.17	1.02	0.54	0.54	1.06	2.12	0.00	0.00	21.07	196.78
13	0.21	74.09	0.31	74.50	0.34	10.41	159.00	1.14	17.39	0.17	1.02	0.54	0.54	1.16	2.32	0.00	0.00	21.27	180.27
14	0.16	54.68	0.18	43.51	0.21	6.46	104.65	1.27	19.27	0.34	2.04	0.68	0.68	1.16	2.32	0.00	0.00	24.31	128.96
15	0.13	45.86	0.18	43.51	0.21	6.46	95.83	1.27	19.27	0.34	2.04	0.68	0.68	1.56	3.12	0.00	0.00	25.11	120.94
16	0.13	45.86	0.18	43.51	0.21	6.46	95.83	1.17	17.75	0.34	2.04	0.68	0.68	1.56	3.12	0.00	0.00	23.59	119.42
17	0.25	86.44	0.28	66.75	0.31	9.42	162.61	1.97	29.94	0.00	0.00	0.53	0.53	0.06	0.12	0.24	0.96	31.55	194.17
18	0.26	91.73	0.27	63.18	0.29	8.66	163.57	1.75	26.60	0.00	0.00	0.53	0.53	0.06	0.12	0.24	0.96	28.21	191.78
19	0.24	82.91	0.26	60.79	0.28	8.36	152.06	0.87	13.22	0.00	0.00	0.53	0.53	0.06	0.12	0.24	0.96	14.83	166.89
20	0.19	65.27	0.37	88.21	0.39	11.86	165.33	0.87	13.22	0.00	0.00	0.03	0.03	0.06	0.12	0.24	0.96	14.33	179.67
21	0.21	74.09	0.37	88.21	0.39	11.86	174.15	0.40	6.08	0.00	0.00	0.03	0.03	0.06	0.12	0.24	0.96	7.19	181.34
22	0.17	59.98	0.32	75.10	0.34	10.18	145.26	0.18	2.74	0.00	0.00	0.03	0.03	0.06	0.12	0.00	0.00	2.89	148.14
23	0.08	28.22	0.22	51.26	0.23	6.84	86.32	0.18	2.74	0.00	0.00	0.03	0.03	0.06	0.12	0.00	0.00	2.89	89.21
Total per day (kWh)	3.43	1,208	5.88	1,402	6.57	200	2,811	19.80	301	3.48	21	8.19	8	14.87	30	1.20	5	365	3,175
Min (kW)	0.03		0.15		0.16			0.18		0.00		0.03		0.06		0.00			52.75
Average (kW)	0.14		0.25		0.27			0.83		0.15		0.34		0.62		0.05			132.30
Max (kW)	0.27		0.37		0.44			1.97		0.36		0.71		1.56		0.24			196.78
Total per year (kWh)		441,044		511,872		72,928	##########		109,850		7,621		2,988		10,855		1,752	133,066	**1,158,910**

Appendix H

Nortek Aquadopp ADCP specifications

Technical Specifications

Water velocity measurement	300m	3000m	6000m
Range:	±5m/s*	±3m/s*	±3m/s*
Accuracy (of measured value ± 0.5cm/s):	1%	1%	1%
Maximum sampling rate (output):	1Hz, 4Hz on request	1Hz	1Hz
Internal sampling rate:	23Hz	23Hz	23Hz
*) Inquire for higher ranges			

Measurement Area	
Measurement cell size:	0.75m
Measurement cell position:	0.35–5.0m (user selectable)
Default position (along beam):	0.35–1.85m
Doppler Uncertainty (noise)	
Typical uncertainty for default configurations:	0.5–1.0cm/s
Uncertainty in U,V at 1Hz sampling rate:	1.5cm/s
Echo intensity	
Acoustic frequency:	2MHz
Resolution:	0.45dB
Dynamic range:	90dB
Sensors	
Temperature:	Thermistor embedded in head
Range:	-4°C to 40°C
Accuracy/resolution:	0.1°C/0.01°C
Time response:	10 min
Compass:	Magnetometer
Accuracy/resolution:	2°/0.1° for tilt <20°
Tilt:	Liquid level
Accuracy/resolution:	0.2°/0.1°
Maximum tilt:	30°
Up or down:	Automatic detect
Pressure:	Piezoresistive
Range:	300m/3000m/6000m
Accuracy/resolution:	0.5% / 0.005% of full scale
Analog inputs	
Number of channels:	2
Voltage supply:	Three options selectable through firmware commands: •Battery voltage / 500 mA •+5V / 250 mA •+12V / 100 mA
Voltage input:	0–5V
Resolution:	16 bit A/D
Data communication	
I/O:	RS232, RS422. Software supports most commercially available USB–RS232 converters
Communication Baud rate:	300–115200 (baud)
Recorder download baud rate:	600/1200 k.Baud for both RS232 and RS422
User control:	Handled via Win32® software, ActiveX® function calls, or direct commands with binary or ASCII data output

Software («Aquadopp / Aquadopp DW»)	
Operating system:	Windows®XP, Windows®7
Functions:	Deployment planning, start with alarm, data retrieval, ASCII conversion. Online data collection and graphical display. Test modes
Data Recording	
Capacity:	9 MB, can add 32/176/352/MB
Data record:	40 bytes
Diagnostic record:	40 bytes
Power	
DC Input:	9–15VDC
Peak current:	3A at 12VDC (user adjustable)
Max consumption 1Hz:	0.2–1.4 W
Avg. consumption:	0.1W (0.02Hz), 0.01W (0.002Hz)
Sleep consumption:	0.0013 W
Transmit power:	0.3–20W, 3 adjustable levels
Battery capacity:	50 Wh
New battery voltage:	13.5 Vdc
Data collection (alkaline):	6 months at 10-min, ±1.5cm/s noise
Data collection (lithium):	18 months at 10-min, ±1.5cm/s noise
Real time clock	
Accuracy:	+/- 1min/year
Backup in absence of power:	4 weeks
Materials	
Standard:	Delrin and titanium.
Connectors	
Bulkhead (Impulse):	MCBH-8-FS, titanium
Cable:	PMCIL-8-MP on 10-m polyurethane cable
Environmental	
Operating temperature:	-5°C to 40°C
Storage temperature:	-20°C to 60°C
Shock and vibration:	IEC 721–3–2
Pressure rating:	0–300m/0–3000m/0–6000m

Dimensions	300m	3000m	6000m
Weight in air:	2.3kg	3.6kg	7.6kg
Weight in water:	Neutral	1.2kg	4.8kg
Cylinder:	see dimensional drawings		

Options	
Battery:	Lithium or lithium Ion
External batteries:	Alkaline, Lithium or Lithium Ion. (See battery brochure for details)
Head configuration:	Inquire

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Appendix I

Measured current velocity data for Panlaitan- day 1

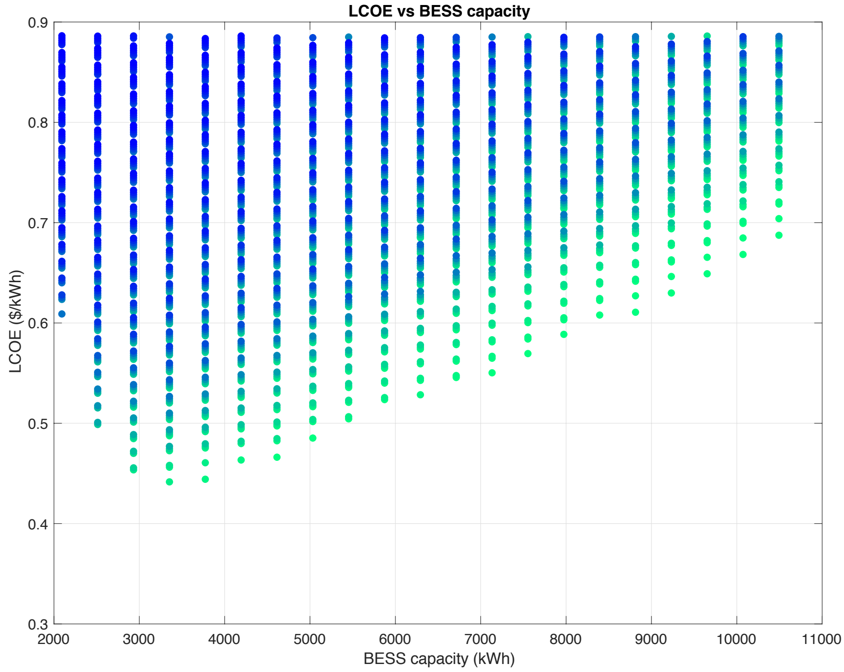
Measurement	Latitude (N)	Longitude €	Depth (m)	Time begin	Time end	Count	Avg. Temp ©	Avg. Speed (m/s)	Avg. Direction (deg)	Std dev. Speed	Std dev. Direction
A1.1	12.08.026	119.51.028	5	811	814	36	31.03389	0.25672	187.27778	0.02076	16.95728
A1.2			10	815	818	32	30.90344	0.28319	141.79375	0.01626	4.58405
A1.3			15	820	823	33	30.70303	0.12379	155.89091	0.01844	10.06784
			20	823	823	6	30.62167	0.10650	202.00000	0.01372	8.90348
A2.1	12.08.066	119.51.277	5	839	842	36	30.86722	0.22867	94.41667	0.04937	11.94146
A2.2			10	843	846	32	30.88125	0.21625	136.88438	0.01464	7.78564
A2.3			15	847	850	36	30.78722	0.13019	177.05000	0.01619	9.83796
			20 M	851	851	5	30.68400	0.09880	200.00000	0.02097	5.22733
A3.1	12.07.879	119.51.282	5	903	906	36	30.72806	0.26214	157.07500	0.01423	4.72515
A3.2			10	907	910	36	30.82944	0.24219	153.51944	0.01814	5.54657
A3.3			15	911	914	33	30.80394	0.13591	177.58788	0.02100	10.60070
			20 M	915	915	8	30.75500	0.14200	197.40000	0.01903	8.68726
			25 M	916	917	12	30.71333	0.12867	216.10000	0.01485	8.82795
A4.1	12.07.799	119.51.153	5	928	931	36	30.70389	0.28161	176.67222	0.01993	21.37496
A4.2			10	932	935	33	30.79576	0.24476	158.03030	0.01711	5.61190
A4.3			15	938	941	36	30.70500	0.13228	180.45000	0.02394	15.05120
A5.1	12.07.553	119.51.099	5	951	954	34	30.65265	0.25388	175.25000	0.04149	11.12693
A5.2			10	955	958	31	30.72742	0.13758	186.09032	0.02542	7.54305
A5.3			15	1000	1003	33	30.67182	0.13067	197.58182	0.05082	10.17830
A6.1	12.07.547	119.51.282	5	1012	1015	35	30.66400	0.24094	141.72286	0.03659	6.92205
A6.2			10	1016	1019	35	30.76171	0.21554	179.20571	0.02051	9.32340
A6.3			15	1020	1023	36	30.74611	0.20489	200.75556	0.03325	11.54577
	12.07.544	119.51.430	Surface	1046	1046	6	30.84500	0.45633	126.31667	0.27501	21.16964
A7.1			5	1033	1036	36	30.86250	0.26289	168.50000	0.02525	11.18726
A7.2			10	1037	1040	29	30.82828	0.24797	192.93793	0.04049	6.22098
A7.3			15	1041	1044	31	30.82000	0.21813	196.44516	0.02069	5.41004
			20	1045	1045	7	30.82000	0.15529	199.04286	0.02591	6.83809
A8.1	12.07.365	119.51.500	5	1057	1060	36	30.55917	0.25106	169.68333	0.01772	4.55804
A8.2			10	1100	1103	31	30.70355	0.26119	178.41935	0.02344	7.95066
A8.3			15	1104	1107	36	30.62139	0.12703	159.67778	0.01906	16.64905
A9.1	12.07.062	119.51.693	5	1131	1134	28	30.17893	0.20811	143.25357	0.02048	6.87876
A9.2			10	1135	1138	32	30.50719	0.13022	155.02500	0.01650	17.03033
A9.3			15	1140	1143	31	30.48742	0.07000	106.68710	0.02512	21.92517
A10.1	12.06.752	119.51.495	5	1153	1156	36	30.38583	0.10050	225.72222	0.01953	31.53088
A10.2			10	1159	1162	36	30.65111	0.06486	163.90278	0.02532	48.04649
A10.3			15	1202	1205	29	30.68690	0.07862	72.87241	0.02155	18.20975
A11.1	12.06.650	119.50.891	5	1310	1313	35	30.46914	0.19917	273.37143	0.03019	9.48856
A11.2			10	1313	1316	29	30.59828	0.22779	276.10345	0.03429	8.28301
A11.3			15	1316	1319	24	30.63583	0.20396	283.83750	0.01627	4.80460
A12.1	12.06.752	119.50.979	5	1328	1331	35	30.62971	0.22757	297.83143	0.02168	4.97214
A12.2			10	1332	1335	36	30.68389	0.21897	301.02222	0.04570	5.86033
A12.3			15	1335	1338	32	30.62813	0.18328	277.27500	0.02111	6.62921
	12.06.662	119.51.999	Surface	1410	1410	4	30.85000	0.43250	294.67500	0.03724	4.44100
A13.1			5	1359	1362	36	30.75306	0.38614	250.94444	0.02986	9.63471
A13.2			10	1402	1405	36	30.79639	0.34203	272.08889	0.02544	4.78902
A13.3			15	1406	1409	36	30.75500	0.31278	293.26389	0.03017	13.52936
A14.1	12.08.291	119.51.300	5	1429	1432	36	31.37917	0.20033	321.34167	0.02574	6.04769
A14.2			10	1433	1436	36	31.13222	0.12567	307.18333	0.03363	12.83668
A14.3			15	1437	1440	36	30.88306	0.14808	307.55000	0.02437	12.78243
A15.1	12.08.272	119.50.878	5	1451	1454	31	31.12677	0.23745	290.90968	0.03082	8.89956
A15.2			10	1455	1458	32	30.99625	0.34953	299.99375	0.02880	11.24521
A15..3			15	1459	1462	34	30.90324	0.31391	335.34118	0.02266	3.72861
	12.06.661	119.51.912	Surface	1527	1527	4	30.50500	0.17	283.30000	0.02251	9.62739
A16.1			5	1531	1534	36	31.01111	0.55	296.71111	0.03281	7.25758
A16.2			10	1535	1538	32	31.04375	0.48	282.09063	0.02347	3.56998
A16.3			15	1539	1542	36	30.94444	0.45	285.48056	0.02055	4.05680

Measured current velocity for Panlaitan-day 2

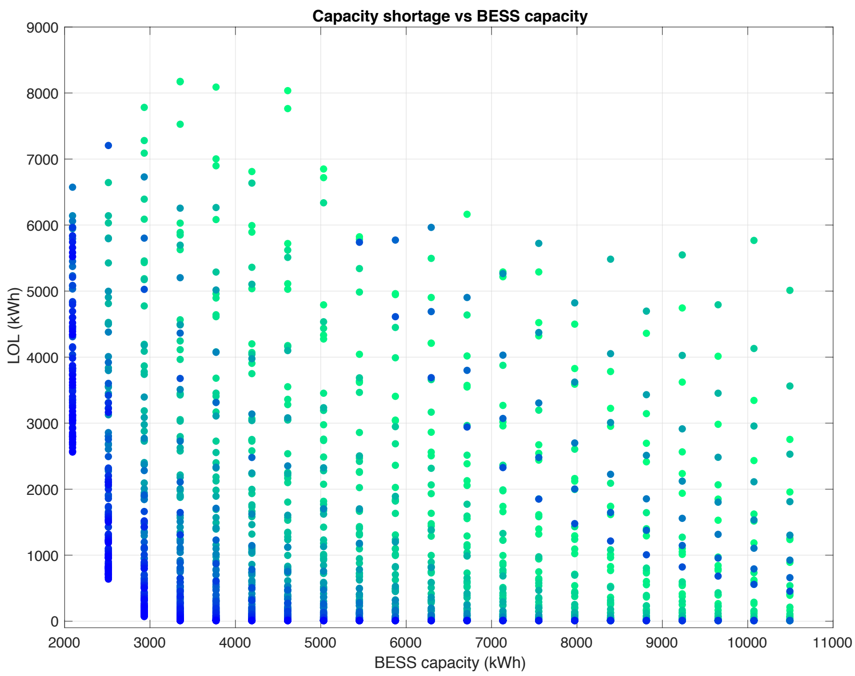
Measurement	Latitude (N)	Longitude €	Depth	Time begin	Time end	Count	Avg. Temp ©	Avg. Speed (m/s)	Avg. Direction (deg)	Std dev. Speed	Std dev. Direction
C1.1	12.06.823	119.52.561	5	816	819	36	28.70417	0.07181	224.08333	0.01932	25.90078
C1.2			10	820	823	35	29.83400	0.04023	241.52571	0.02181	51.09552
C1.3			15	824	827	33	30.19909	0.03791	151.10606	0.02089	55.48240
C2.1	12.06.656	119.52.139	5	843	846	36	29.91056	0.05717	67.80833	0.02244	41.38412
C2.2			10	847	850	36	30.40611	0.12875	65.25833	0.01862	15.15973
C2.3			15	851	854	36	30.51667	0.16300	111.57222	0.01534	5.61191
C3.1	12.06.315	119.51.041	5	908	911	36	30.59167	0.08844	156.61111	0.01558	12.41660
C3.2			10	912	915	36	30.68167	0.09933	102.02500	0.02341	9.22727
C3.3			15	916	919	36	30.69306	0.08094	96.26944	0.02781	15.29444
C4.1	12.06.242	119.51.519	5	930	933	35	30.80029	0.15851	112.23143	0.01936	15.83183
C4.2			10	934	937	35	30.84000	0.12420	88.25429	0.01986	7.99093
C4.3			15	938	941	35	30.82457	0.17369	96.54857	0.02127	6.78460
C5.1	12.05.954	119.50.929	5	956	959	36	30.38389	0.08719	127.78889	0.03123	45.97223
C5.2			10	1000	1003	36	30.61167	0.05431	224.05833	0.04835	99.86449
C5.3			15	1004	1007	36	30.61917	0.07156	244.44444	0.02454	61.17022
C6.1	12.06.648	119.50.592	5	1031	1034	36	30.03167	0.17167	142.48056	0.05830	63.71559
C6.2			10	1035	1038	35	30.46686	0.15137	145.06286	0.05869	76.50491
C6.3			15	1039	1042	36	30.58056	0.11256	136.12500	0.05684	67.63897
C7.1	12.08.399	119.50.712	5	1135	1138	36	29.22667	0.22386	95.45833	0.10776	24.92887
C7.2			10	1139	1142	33	29.96606	0.20185	129.83939	0.03943	30.57374
C7.3			15	1142	1145	36	30.23833	0.17808	111.74444	0.02083	17.59984
C8.1	12.08.491	119.51.034	5	1202	1205	36	29.15278	0.30683	97.54444	0.03419	12.15647
C8.2			10	1206	1209	36	30.09472	0.23597	94.87500	0.03849	25.82460
C8.3			15	1210	1213	36	30.29500	0.14428	111.99444	0.01916	15.43847
C9.1	12.08.54.6462	119.50.33.8316	5	1300	1303	31	28.95000	0.11894	102.40968	0.04028	17.53051
C9.2			10	1304	1307	36	30.01083	0.10789	96.28056	0.02147	11.94781
C9.3			15	1308	1311	36	30.25861	0.08611	123.92500	0.02771	39.33113
C10.1	12.09.039	119.50.479	5	1324	1327	35	29.50457	0.03797	247.40857	0.01473	66.10259
C10.2	(12.09.18.4602)	(119.50.26.6316)	10	1328	1331	36	30.28806	0.04972	119.11667	0.01742	32.21736
C10.3			15	1332	1335	36	30.43778	0.10225	62.60833	0.02173	13.72746
C11.1	12.05.881	119.50.717	5	1407	1410	30	28.51500	0.12780	247.41667	0.03471	15.81710
C11.2			10	1411	1414	36	29.71167	0.12989	280.51667	0.02799	16.60510
C11.3			15	1415	1418	36	30.11528	0.12350	288.81389	0.02086	13.34079
C12.1	12.06.591	119.52.021	5	1435	1438	35	29.16229	0.17820	168.90000	0.02855	123.74999
C12.2			10	1439	1442	36	30.04833	0.16625	306.38056	0.02199	8.33920
C12.3			15	1443	1446	35	30.30714	0.09229	311.20571	0.01653	14.18605

Appendix J

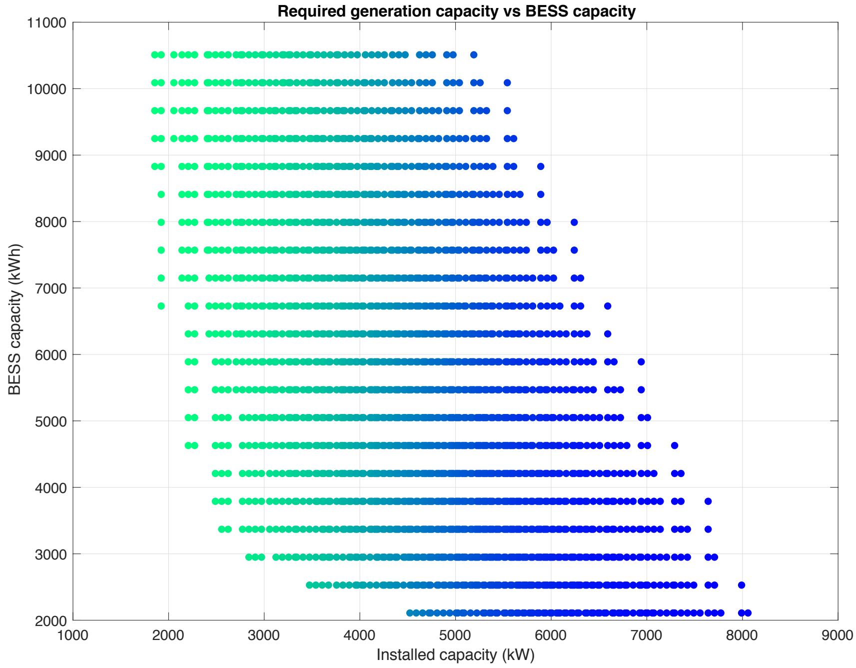
HOMER-pro optimization results of KPI plotted against BESS capacity.



A clear optimum is seen for the required BESS capacity in relation to the LCOE. Any further increase of BESS for this particular system would not result in more effective energy use or lower LCOE values.



Within a range of 200-3500 kW installed BESS capacity a sharp decrease can be seen in the LOL. This indicates the active role the BESS plays in the dependable capacity of this FRES. Shifting the importance from dependable generation to dependable storage.



The decrease in BESS capacity here levels at an installed generation capacity of around 4500 kW (or more). The effective point of generation capacity and storage capacity integration lies within this range and indicates the boundary values of useful implementation.

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